

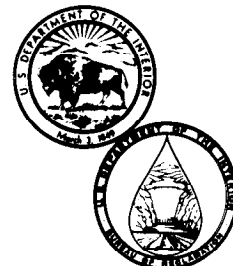
**REC-ERC-89-4**

# **INVESTIGATION OF ALKALI-SILICA REACTIVITY IN FOUR DAMS IN THE SOUTHEASTERN UNITED STATES**

**Denver Office**

**July 1989**

**U. S. Department of the Interior  
Bureau of Reclamation**



TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. REC-ERC-89-4	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE INVESTIGATION OF ALKALI-SILICA REACTIVITY IN FOUR DAMS IN THE SOUTHEASTERN UNITED STATES	5. REPORT DATE JULY 1989	6. PERFORMING ORGANIZATION CODE D-3731
	8. PERFORMING ORGANIZATION REPORT NO. REC-ERC-89-4	
7. AUTHOR(S) David Stark	10. WORK UNIT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Construction Technology Laboratories 5420 Old Orchard Road Skokie IL 60077	11. CONTRACT OR GRANT NO. 5-CP-81-06560	
	13. TYPE OF REPORT AND PERIOD COVERED	
12. SPONSORING AGENCY NAME AND ADDRESS Bureau of Reclamation Denver Office Denver CO 80225	14. SPONSORING AGENCY CODE DIBR	
	15. SUPPLEMENTARY NOTES Microfiche and hard copy available from Denver Office, Denver, Colorado.	
16. ABSTRACT This investigation of the alkali-silica reactivity of four dams in the southeastern United States supplements a similar study on five dams in southwestern United States. The investigations involved an onsite inspection and laboratory studies of concrete cores. The investigative procedures included petrographic examination, relative humidity measurements, length changes of cores exposed to moist air at 100 °F and to sodium hydroxide solution, and osmotic cell measurements. A comparison of observations on the southeastern and the southwestern dams is made. The manifestations of distress due to the reaction are similar, and the effects of alkali content of the cement, different types of reactive aggregates, surface drying, and climate exposure conditions are noted.		
17. KEY WORDS AND DOCUMENT ANALYSIS a. DESCRIPTORS-- *alkali-silica reactivity/ *alkali-aggregate reactions/ concrete/ concrete cores/ aggregates/ petrographic investigations/ concrete dam  b. IDENTIFIERS-- Fontana Dam, NC/ Hiwassee Dam, NC/ New Savanna Bluff Lock and Dam, GA/ Oliver Lock and Spillway, AL c. COSATI Field/Group 08D COWRR: 0804 SRIM:		
18. DISTRIBUTION STATEMENT Available from the National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia 22161.	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 42
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE

Ed:REC

**REC-ERC-89-4**

**INVESTIGATION OF ALKALI-SILICA  
REACTIVITY IN FOUR DAMS IN  
THE SOUTHEASTERN UNITED STATES**

by

**David Stark**

**Prepared Under Contract  
No. 5-CP-81-06560**

**JULY 1989**

**Concrete and Structural Branch  
Research and Laboratory Services Division  
Denver Office  
Denver, Colorado**

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

The research covered by this report was funded under the Bureau of Reclamation Program Related Engineering and Scientific Studies Allocation No. DR-441, "Repair of Concrete Affected by Alkali-Aggregate Reaction."

The information contained in this report regarding commercial products or firms may not be used for advertising or promotional purposes and is not to be construed as an endorsement of any product or firm by the Bureau of Reclamation.

The information contained in this report was developed for the Bureau of Reclamation; no warranty as to the accuracy, usefulness, or completeness is expressed or implied.

# CONTENTS

	Page
Introduction .....	1
Conclusions .....	1
Fontana Dam .....	1
Hiwassee Dam .....	1
New Savannah Bluff Lock and Dam .....	2
Oliver Lock and Spillway .....	2
Investigative procedures .....	2
Relative humidity measurements .....	2
Length change of concrete cores .....	3
Petrographic examination .....	4
Osmotic cell data .....	4
Discussion of results .....	5
Fontana Dam .....	5
Hiwassee Dam .....	5
New Savannah Bluff Lock and Dam .....	6
Oliver Lock and Spillway .....	7
Osmotic cell tests .....	7
Summary .....	8
Bibliography .....	9
Appendix A – Fontana Dam .....	11
Appendix B – Hiwassee Dam .....	17
Appendix C – New Savannah Bluff Lock and Dam .....	23
Appendix D – Oliver Lock and Spillway .....	31
Appendix E – Osmotic cell data .....	37



## INTRODUCTION

This report describes an investigation into the development of alkali-silica reactivity in concrete in four dams located in southeastern United States. The following structures were investigated:

1. Fontana Dam—near Fontana, North Carolina;
2. Hiwassee Dam—near Murphy, North Carolina;
3. New Savannah Bluff Lock and Dam—near Augusta, Georgia; and
4. William Bacon Oliver Lock and Spillway—near Tuscaloosa, Alabama (hereafter identified as Oliver Lock and Spillway).

Each of these structures had been investigated previously for cracking and other effects due to alkali-silica reactivity. Reports on these investigations, developed by the United States Army Corps of Engineers Waterways Experiment Station [1-5]\*, have been used for background information.

The present investigation was directed toward determining remaining potential for expansive alkali-silica reactivity, and identifying factors contributing to reactivity. The investigation was based on the determination of relative humidities at several locations in the dams, and on laboratory testing of a limited number of concrete cores taken from the dam. Results from this study can be used for guidance in possible rehabilitation or reconstruction needs in the future.

## CONCLUSIONS

Following are conclusions drawn from findings of this investigation. These conclusions are based on results of a limited number and size of concrete samples from various locations in the structures, and, therefore, may not necessarily apply to the structure as a whole.

### Fontana Dam

1. Alkali-silica reactivity has occurred in concrete in this dam, but severity of the reaction appears to vary significantly from area to area. Severe reactivity with attendant expansion and cracking has developed near the top of the dam, i.e., at the roadway, but it appears to have produced little or no differential volume change and cracking in concrete cores from interior and lower portions of the dam.

2. Potential for further expansive alkali-silica reactivity appears to exist in cores from Fontana Dam.

3. The primary reacted rock type is a metagraywacke to quartzite aggregate. Minor amounts of schist also have reacted. All are present in both the coarse and fine aggregate.

4. Nearly all of the concrete in the dam is still sufficiently damp to permit expansive reactivity to occur. Only concrete tested within a few inches of surfaces exposed to ambient conditions at upper, interior locations in the dam appears to be sufficiently dry to preclude expansive reactivity.

5. Concrete near the roadway at the top of the dam, and in adits at elevations 1315 and 1700, contains aggregate with potential for expansive reactivity. The greatest potential appeared to exist in concrete cores from near the roadway at the top of the dam, despite the finding that, to date, the most severe reactivity appears to have already occurred at that location.

6. Concrete near the roadway and at upper interior locations in the dam appears to contain alkali available for continued expansion and abnormal differential volume change due to alkali-silica reactivity.

### Hiwassee Dam

1. Alkali-silica reactivity has occurred in concrete in Hiwassee Dam. The most severe reactivity, accompanied by cracking and abnormal expansion, has occurred near the roadway at the top of the dam. Degree of reactivity, with little or no expansion or differential volume change, appears to have been minor in concrete at low levels in the dam.

2. Metagraywacke, quartzite, and schist, which occur in both the coarse and fine aggregate, have reacted to produce excessive expansion and cracking.

3. Concrete in virtually all portions of the dam investigated is still sufficiently damp to permit expansive alkali-silica reactivity to occur.

4. Little, if any, unreacted but potentially reactive aggregate remains in concrete cores near the roadway at the top of the dam where the most severe reactivity has already occurred. Unreacted but potentially reactive aggregate appears to still be present in cores from lower elevations in the dam. However, little, if any, expansive reactivity thus far appears to have developed in cores at these elevations.

---

\* Numbers in brackets refer to entries in bibliography.

5. Sufficient alkali is still present in cores from lower levels of the dam to permit potentially expansive alkali-silica reactivity to occur. Alkali available for expansive reactivity in cores from near the top of the dam appears to be depleted.

#### **New Savannah Bluff Lock and Dam**

1. Expansive alkali-silica reactivity, with attendant cracking, has occurred to varying degrees in this structure.

2. The primary reacted aggregate component was quartzite which constitutes 30 to 65 percent of the coarse aggregate. Granite gneiss, which composes the remainder of the coarse aggregate, also appears to have reacted, but conclusive evidence suggesting expansive or deleterious reactivity associated with this rock type was not observed. It is suggested that this is due to more rapid reaction of chert and quartzite, thereby leaving little alkali available at later ages for deleterious reactivity involving granite gneiss.

3. Concrete in the lock and dam structure, including near-surface locations, was sufficiently damp to permit expansive reactivity to occur.

4. Concrete cores taken from this structure appear no longer to contain unreacted but potentially reactive aggregate.

5. Alkali available to sustain expansive reactivity in the cores taken from this structure appears to have been depleted.

#### **Oliver Lock and Spillway**

1. Severe alkali-silica reactivity with attendant expansion and cracking has occurred to varying degrees in the lock walls. Cracking in the landside wall was most severe at the top surface but was minor at lower, interior, locations in the wall. Cracking in the riverside wall was minor but variable.

2. The reacted aggregate component is chalcedonic chert which constitutes 35 to 50 percent of the coarse aggregate.

3. Measurements indicated that concrete near the top surface of both lock walls appears to be sufficiently damp to sustain expansive alkali-silica reactivity. Concrete 10 feet below the top surface of the landside wall and up to 8 inches inward from the south face of the landside wall was found to be too dry to support expansive reactions.

4. There appears to be little, if any, unreacted but potentially reactive aggregate remaining in concrete

cores from near the stairway landing of the landside lock wall.

5. Alkali available for expansive reactivity to occur in concrete cores from the landside wall of the lock appears to be depleted.

### **INVESTIGATIVE PROCEDURES**

Three test procedures were used to characterize the state of alkali-silica reactivity in the four structures. In addition, an osmotic cell test procedure was used to provide information on whether alkali determinations would be useful in assessing potential for remaining expansive alkali-silica reactivity in concrete structures. These procedures are described below.

#### **Relative Humidity Measurements**

Relative humidity measurements were made to determine whether sufficient moisture is available in the concrete to permit expansion due to alkali-silica reactivity. Previous work at Construction Technology Laboratories, Inc. (CTL) revealed that expansions can develop if relative humidities in concrete are greater than 80 to 85 percent, referenced to 70 to 75 °F. The findings were based on comparisons of length changes of mortar bars containing high-alkali cement plus reactive aggregate, with mortar bars containing the same cement and water-cement ratio, but known nonreactive aggregate. After storage of reactive combinations over water in sealed containers held at 100 °F to obtain 0.10 percent expansion, specimens (including nonreactive controls) were then transferred to various relative humidity conditions between 35 and 100 percent at 40, 73, and 100 °F until constant lengths were measured. Plots against relative humidity of differences in length change between the reactive and nonreactive cement-aggregate combinations then established the minimum relative humidity at which expansion of the reactive combinations exceeded those of the nonreactive combinations. As stated above, the minimum relative humidity above which net expansions developed was 80 to 85 percent. It was also found that reactive combinations produced greater shrinkages than nonreactive combinations at relative humidity levels less than 80 to 85 percent. This reflects loss of water and shrinkage of existing alkali-silica gel.

These findings support those of other investigators, who found that large moisture uptake and expansion of various alkali-silica gels occur at relative humidity levels greater than about 85 percent [6,7]. Thus, the relative humidity criterion used in this study, above which expansion due to uptake of moisture by existing gel reaction products occurs, was taken as 85 percent, referenced to 70 to 75 °F.



Relative humidity measurements were made using a technique developed and previously used in field structures by CTL. The procedure also was used in the investigation of dams by Stark [8]. This technique consists of drilling powder samples from the concrete using a 1-inch-diameter carbide-tip bit and an electrically driven impact drill. The powder sample thus produced is caught during drilling by a small rubber cup which slips over the drill bit and is pressed against the concrete surface from which the sample is procured. In this position, the cup also prevents the powder from measurable drying during the drilling operation.

Once collected in the rubber cup, the powder sample is quickly transferred to a 100-cc polypropylene bottle which is immediately tightly capped to prevent drying. The bottle containing the powder sample is then transferred to storage at 70 to 75 °F for relative humidity measurement at that temperature range.

Actual relative humidity measurements are made using a Monfore relative humidity probe developed at the Portland Cement Association [9]. This probe is, in effect, an electrical strain gauge, in which a short Dacron thread is attached to one end of a 0.001-inch-diameter advance wire. When exposed to a particular environment, the Dacron thread lengthens or shortens in response to sorption of moisture in the environment. This changes the length, thus the diameter, of the advance wire and, in turn, results in a change in electrical resistance of the wire. Through previous calibration, and the use of a null indicator, the relative humidity "seen" by the Dacron thread is read directly from a dial on a galvanometer in the electrical measuring circuit. About 10 minutes are required for the probe to reach equilibrium with the surrounding environment.

In this investigation, the relative humidity of the powder sample in the sealed bottle was measured in situ by inserting the probe into the bottle. For this purpose, the original cap on the bottle is quickly replaced by one that contains a tightly fitting 5/32-inch-diameter brass tube that extends through the cap. Once this cap is in place, the relative humidity probe is immediately slip-fitted through the brass tube and positioned over the powder in the sealed bottle until equilibrium (stable relative humidity reading) is reached. The indicator on the galvanometer is then adjusted until the null indicator reads "zero". The relative humidity is then read from the galvanometer dial.

The overall procedure involves transfer of powder from the rubber cup to a plastic bottle, and exchange of caps while the sample is in the bottle. Thus, the powder sample is exposed to ambient conditions for two short periods of time, usually no more than 2 to 3 seconds each. Various trial procedures have

indicated that 20 to 30 seconds exposure is required to change the measured relative humidity of the sample one percentage point. Also, the drilling process has not been found to change the relative humidity of the powder sample. The accuracy of the entire procedure was determined not to differ more than about one percent compared with in-place measurements (probe inserted into tube in undisturbed concrete) of relative humidity.

The procedure used in the present investigation was adapted to obtain relative humidity profiles with depth into the concrete. This was done by procuring powder samples at selected depth intervals, using a single drill hole. For each sample, a 1/2-inch depth of concrete was drilled, from which the powder was obtained. Relative humidity profiles were developed from samples taken, in most cases, at intervals of 1/2 to 1, 2 to 2-1/2, 4 to 4-1/2, 8 to 8-1/2, 16 to 16-1/2, and 24 to 24-1/2 inches. A 1/2-inch sample "thickness" has been found to be suitable for this purpose. Powder samples obtained between these depths were discarded. Prior to drilling for a test sample, the hole was carefully cleaned to avoid contamination.

To determine whether expansion due to alkali-silica reactivity is liable to occur at a sampled location, comparison was made between the 85 percent threshold relative humidity level and the reading obtained on the powder sample. If the relative humidity of the powder sample was greater than the threshold value, expansion due to reactivity was then considered possible.

All samples and relative humidity measurements were taken during the period of November 19 to 23, 1985.

### **Length Change of Concrete Cores**

Concrete cores ranging from 3 to 4 inches in diameter were taken at selected locations in each structure. These cores were utilized to determine potential for expansion due to continued alkali-silica reactivity and for petrographic examination. All concrete cores were procured during the autumn of 1985.

Testing for length change consisted of immersing cores in IN NaOH solution, and immersing "companion" cores in water, both in sealed containers held at 100 °F. Additional cores were stored over water in sealed containers held at 100 °F. Companion cores in these tests were taken either at side-by-side locations in the dam, or from the same core hole, but not necessarily at exactly the same depth into the structure.

For these tests, particular effort was made to obtain core sections 10 to 11 inches long. However, due to cracking in the cores as received, intact cores were limited to 6 to 10 inches in length. All core sections were sawed transversely and fitted at each end with gauge points. Weight and length measurements were made prior to testing. Weights were measured to the nearest gram and lengths were measured to the nearest 0.0001 inch.

As noted above, companion cores were stored over water, in water, or in 1N NaOH solution. Storage over water was used to provide an indication of potential for expansion with available alkali still present in the concrete. Immersion in water was used to determine length and weight changes due to rewetting partially dried concrete. Equilibrium in water was identified when the cores reached constant ( $\pm 1$  gram) weight. This point was taken as a reference to assess remaining potential for expansion due to additional alkali-silica reactivity in the companion cores immersed in 1N NaOH solution or stored over water.

Immersion of cores in 1N NaOH solution was intended to "force" expansive alkali-silica reactivity if potential remained for that reaction to occur. Differences in expansion between the core in 1N NaOH solution and the companion core immersed in water were taken to reflect that potential. Differences in expansion were judged to be significant i.e., that developed in 1N NaOH solution exceeded that developed in water by at least 0.02 percentage points. Six to eight months were considered sufficient test time to establish meaningful trends.

Several interpretations of results of these tests are possible. Expansions of cores immersed in 1N NaOH solution that are more than about 0.02 percentage points greater than those of companion cores immersed in water suggest that unreacted but potentially reactive silica is still present in the concrete structure. Conversely, lack of significant expansion of cores stored in 1N NaOH solution suggests that potentially reactive silica is no longer present to produce additional expansive reactivity in the concrete, regardless of alkali availability. If expansion of cores stored over water is not significantly greater than that of companion cores immersed in water, then it is concluded that sufficient alkali is no longer present to combine with potentially reactive silica to produce excessive expansion in the concrete structure, provided that potentially reactive silica is still present.

#### **Petrographic Examination**

Several core sections from each structure were examined microscopically to assess the development

of alkali-silica reactivity, and to identify the reacted components of the aggregate. Each of these core sections was sawed longitudinally, and one sawed surface was finely lapped to better reveal the microstructure of the concrete and manifestations of reactivity. The other half of each core was used to examine freshly fractured surfaces for further evidence of reactivity. The core sections were examined under a stereomicroscope using 7 to 35 magnification. Supplementary observations were made using a petrographic microscope.

#### **Osmotic Cell Tests**

Osmotic cell tests were run on a known highly reactive feldspathic sand to determine the relative importance of various solutions in supporting expansive reactivity in concrete. The osmotic cell partially simulates a paste-aggregate interface [10]. It is made of Lucite, and consists of a 2-inch-diameter by 3/4-inch-deep reaction chamber and a reservoir chamber of the same size separated by a 1/4-inch-thick, well-hydrated, cement paste membrane of 0.55 water-cement ratio. Both chambers are filled with test solution. The reaction chamber contains, in addition, 12 grams of washed test aggregate ground to the No. 50 to + No. 100 sieve size. A vertically oriented capillary tube is fitted through the top of each chamber, with both tubes being partially filled to the same height with test solution. If expansive reaction occurs between the solution and the aggregate in the reaction chamber, solution flows from the reservoir chamber, through the paste membrane, and into the reaction chamber. This is known as positive flow and produces a height differential between menisci in the two capillary tubes which is taken as a measure of potential for reactivity. Based on field performance, positive flow rates that exceed 2.0 millimeters per day for 1N NaOH solution are considered to reflect potential for deleterious alkali-silica reactivity.

In this investigation, the following solutions were evaluated with respect to their effect on alkali-silica reactivity in the osmotic cell.

##### **1.0N NaOH**

Saturated  $\text{Ca}(\text{OH})_2$

Saturated  $\text{Ca}(\text{OH})_2$  + 0.2N NaOH

Saturated  $\text{Ca}(\text{OH})_2$  + 0.5N NaOH

Saturated  $\text{Ca}(\text{OH})_2$  + 1.0N NaOH

Saturated  $\text{Ca}(\text{OH})_2$  + 0.1N NaOH + 0.1N KOH

Saturated  $\text{Ca}(\text{OH})_2$  + 0.25N NaOH + 0.25N KOH

Saturated  $\text{Ca}(\text{OH})_2$  + 0.5N NaOH + 0.5N KOH

Saturated  $\text{Ca}(\text{OH})_2$  + 0.2N  $\text{Na}_2\text{SO}_4$

Saturated  $\text{Ca}(\text{OH})_2$  + 0.5N  $\text{Na}_2\text{SO}_4$

Saturated  $\text{Ca}(\text{OH})_2$  + 1.0N  $\text{Na}_2\text{SO}_4$

To allow definitive trends to develop, the osmotic cell test period was extended to 66 days, which is

about 30 days beyond the usual period for evaluating aggregates for potential reactivity in 1N NaOH solution.

## DISCUSSION OF RESULTS

Results of work carried out in this investigation are given in appendixes A through E. Individual discussions of results for each dam and for the osmotic cell tests are given below.

### Fontana Dam

**Relative Humidity Measurements.** — Results of relative humidity measurements are given on figure A1 in appendix A. These results indicate that, except for near-surface concrete at one location, concrete from exposed surfaces inward is sufficiently damp to permit expansive alkali-silica reactivity to occur. Concrete in the adit at elevation 1315 was at or near 100 percent relative humidity (referenced to 70 to 75 °F) from the exposed surface inward to the 24-inch depth. This is well above the 80 to 85 percent relative humidity threshold level required for expansive reactivity. In the adit at elevation 1700, concrete from the exposed surface inward to a depth of 4 inches increased from 55 to 85 percent. At greater depths up to 24 inches, relative humidity values gradually increased to 100 percent.

These three locations were considered to characterize the range of moisture conditions in the dam. Thus, essentially all of the concrete in the dam is considered to be sufficiently damp to permit expansive reactivity to occur, provided other reactivity requirements are met.

**Petrographic Examination of Concrete Cores.** — Results of petrographic examinations are given in table A1. Concrete cores from three locations in the dam were examined microscopically for evidence of alkali-silica reactivity. Evidence for the reaction varied considerably among these locations.

In block 35 at the top of the dam, prominent large-scale map cracking was evident on the roadway surface. The core examination revealed the development of severe alkali-silica reactivity, as evidenced by reaction rims in the aggregate, microcracks associated with the aggregate, and the presence of copious amounts of alkali-silica gel in microcracks in the mortar, in reacted aggregate particles, and in entrapped air voids and aggregate sockets.

In cores taken in the adits at elevations 1315 and 1700, evidence of alkali-silica reactivity was meager to nonexistent. In concrete from the adit at elevation 1315, coarse aggregate particles displayed reaction rims. Minor microcracking was observed within reacted particles, and occasional gel deposits were

found in entrapped air voids. No abnormal cracking was found in the mortar. Evidence of reactivity in concrete from the adit at elevation 1700 was nonexistent. Only a few discontinuous reaction rims were observed in a few darker schistose-type particles. Gel deposits were not observed.

Thus, the severity of reactivity evidently varies significantly with location in the dam. These variations correspond to the severity of map cracking observed on exposed surfaces of the dam. On the roadway, severe map cracking was observed while, at the adit locations, surface cracking was not observed.

**Length Change of Concrete Cores.** — Results of length change measurements on concrete cores are given in table A2 and on figure A2. These results indicate that unreacted but potentially reactive aggregate is still present in concrete at all three core locations, regardless of severity of previous reactivity (e.g., roadway concrete vs. adit concrete). This is evidenced by the steady increase in expansion of cores immersed in 1N NaOH solution, compared with cores stored in or over water. In the latter two environments, core expansions stabilized after 1 month. This expansion was due to uptake of moisture from the dry condition. These data suggest that additional alkali, provided by the 1N NaOH solution, was required to produce measurable expansion of the cores, whereas, those stored over water had stabilized. This implies that, at least for concrete cores from the roadway and from the adit at elevation 1700, alkali required for expansive reactivity in these cores had become depleted.

### Hiwassee Dam

**Relative Humidity Measurements.** — Results of relative humidity measurements are given on figure B1 in appendix B. These data indicate that concrete at depths from exposed surfaces inward are sufficiently damp to sustain expansive alkali-silica reactivity. This is evidenced by all relative humidity values being at or above the 80 to 85 percent threshold level required for expansion to occur. Based on these investigations, these high relative humidity values would be expected to be encountered only at depths greater than about 6 to 12 inches from exposed surfaces. However, relative humidity values for the 15-inch-thick wall along the roadway at the top of the dam also were well above the threshold level. This indicates that little or no long-term atmospheric drying can be expected at this damsite.

**Petrographic Examination of Concrete Cores.** — Results of petrographic examinations of two cores are given in table B1. Observations indicate that alkali-silica reactivity has occurred to varying

degrees within the dam. Evidence of severe reactivity was observed in the core taken in the roadway at the top of the dam. Here, well-defined reaction rims were observed in reacted metagraywacke and schist coarse and fine aggregate particles. Gel reaction products were observed in entrapped air voids, in microcracks in the mortar and in aggregate, and in aggregate sockets. Microcracks that extend from reacted particles into surrounding mortar attest to the expansive nature of the reaction. In contrast, the concrete core from the adit at elevation 1312 revealed only faint discontinuous rims in reacted particles and very little microcracking in the aggregate and surrounding mortar. Alkali-silica gel deposits were meager and were found only in isolated entrapped air voids.

The severity of alkali-silica reactivity observed in the cores appeared to correlate with the severity of map cracking observed on exposed concrete surfaces in the dam. Prominent map cracking was observed in the roadway wall sampled for relative humidity measurements, and in the roadway, while only faint, localized map cracking was noted at the adit location from where a core was taken.

The most severe cracking due to reactivity appears to have developed near the top of the dam where less restraint to movement exists, and where consequent greater development and opening of cracks and more rapid penetration of atmospheric moisture into the concrete can occur.

Similar patterns of reactivity appear to have developed in both Hiwassee Dam and nearby Fontana Dam.

**Length Change of Concrete Cores.** — Results of length change measurements on cores taken from Hiwassee Dam are given in table B2 and on figure B2. These results indicate that there is little unreacted but potentially reactive aggregate remaining in these cores, regardless of apparent previous degree of reaction. This is evidenced by the only slightly greater rate of expansion of cores immersed in 1N NaOH solution compared with those for cores stored in or over water. If such aggregate is present at all, it would appear to be in slightly greater amount in concrete cores from near the adit at elevation 1312 compared with cores from the roadway. The data further indicate that little alkali is presently available to sustain expansive, deleterious, reactivity in the cores. This is based on the lack of continued expansion of cores stored over water after the initial expansion due to absorption of water by dried concrete. Collectively, the data indicate limited potential in the cores for continued expansion due to alkali-silica reactivity, even under moist exposure condition favorable to such reaction.

## **New Savannah Bluff Lock and Dam**

**Relative Humidity Measurements.** — Results of relative humidity measurements are given on figures C1 and C2 in appendix C. At all locations, relative humidity values were uniformly high and well above the 80 to 85 percent threshold level required for expansive reactivity. Only in surface concrete up to the 2-inch depth were relative humidity levels slightly below those at greater depths up to 24 inches. The trend in the curves indicates that concrete at depths greater than 24 inches is at 95 to 100 percent relative humidity. Since it is believed that the locations sampled include the range of moisture conditions at this site, it is concluded that concrete in the lock and dam structure is still sufficiently damp to permit expansive alkali-silica reactivity to occur.

**Petrographic Examination of Concrete Cores.** — Results of the petrographic examination of three cores from different locations are given in table C1. Evidence indicating alkali-silica reactivity as a major cause of the observed cracking was meager. Microcracking attributable to reactivity was not confirmed. Partial and full, well-defined, reaction rims were observed to varying degrees in crushed granite gneiss particles and, particularly, in quartzite gravel particles. Alkali-silica gel deposits were comparatively minor, with the greatest amounts of gel occurring in the core from the top of the pier nearest the lockmaster's house. Here, and, to a lesser extent, in cores from the south abutment, gel was found in entrapped air voids and aggregate sockets associated primarily with quartzite particles. Alkali-silica gel deposits were not found in the core from the lock wall where well-defined map cracking has developed. Although granite gneiss particles displayed reaction rims, and sockets formed by these particles contained traces of gel, it is believed that only very minor reactivity involving this rock type has occurred. By comparison, severity of reactivity involving quartzite particles appeared to be much greater, even though damage (cracking) directly associated with reactivity was essentially absent in these cores.

Observed differences in degree of reactivity between the chert and quartzite and the granite gneiss may reflect greater rates of reactivity of the chert and quartzite, thereby resulting in lesser alkali being available for reaction with granite gneiss.

**Length Change of Concrete Cores.** — Results of length change measurements on concrete cores are given in table C2 and on figure C3. These results indicate little or no potential for expansion exists due to continued alkali-silica reactivity, and that essentially no unreacted but potentially reactive aggregate is present in the cores. This is revealed

by the absence of continued expansion of the cores in 1N NaOH solution or water after the initial expansion due to uptake of moisture at 1 month. If reactive silica was still present, it would be anticipated that, with the addition of 1N NaOH, significant differential expansions would have developed within the 7-month test period.

### Oliver Lock and Spillway

**Relative Humidity Measurements.** — Results of the relative humidity measurements are given on figure D1 in appendix D. At locations in the landside and in the riverside lock walls, relative humidity values increased from about 80 to nearly 100 percent within 2 to 4 inches from top exposed concrete surfaces, and remained at that level to the 16-inch maximum depth sampled. This trend in the data indicates that concrete at these and greater depths is sufficiently damp to support expansive reactivity if other requirements are met. In contrast, data for the sample location in the landside lock wall, about 10 feet below the top surface, indicate relative humidity values ranging from about 70 to 80 percent up to the 8 inches depth. This is sufficiently dry to preclude expansive reactivity at least up to this depth. From the trend indicated on figure D1, based on previous experience, it is likely that relative humidity values exceed the 80 to 85 percent relative humidity threshold level at greater depths, thus permitting expansive reactivity to occur.

**Petrographic Examination of Concrete Cores.** — A summary of petrographic observations on two cores is presented in table D1. In core B, taken in the landside lock wall, evidence of severe alkali-silica reactivity was observed. Large amounts of alkali-silica gel, well-defined reaction rims on aggregate particles, and microcracks extending from reacted aggregate particles into surrounding mortar, attest to the expansive nature of the reaction.

In contrast, core C, taken vertically into the riverside wall of the lock, in an area with only minor visible cracking, failed to display abnormal microcracking and evidence of distress in the paste matrix of the concrete. Dense clarified rims which are believed to have formed in the concrete, were observed on numerous chert particles and on a few sandstone aggregate particles. Extensive deposits of alkali-silica gel were found in entrapped air voids. A few microcracks were observed within rimmed aggregate particles but they were free of gel deposits. The difference in severity of reactivity noted might be attributable to differences in cements with reported different alkali contents.

**Length Change of Concrete Cores.** — Results of length change measurements on concrete cores are given in table D2 and on figure D2. Comparison

shows that cores immersed in 1N NaOH solution produced only slightly greater expansions than cores stored in or over water. This indicates little or no potential for further expansive reactivity in these cores. This may be due to lack of available alkali, and possibly to a lack of remaining unreacted but potentially reactive aggregate. After initial expansions, which were due to uptake of moisture from the dried condition, core lengths remained relatively stable.

### Osmotic Cell Tests

Results of the osmotic cell tests are summarized on figures E1 to E3 in appendix E, where flow is plotted against time for the various solutions. Relationships between flow differential after the 66-day test period and concentration of NaOH, NaOH + KOH, and  $\text{Na}_2\text{SO}_4$  in solutions saturated with  $\text{Ca}(\text{OH})_2$  are shown on figure E4.

Comparison of data on figure E1 indicates, as would be expected, that increasing concentration of NaOH solution increased the flow rate for the reactive aggregate tested. Solutions containing only  $\text{Ca}(\text{OH})_2$  or  $\text{Ca}(\text{OH})_2 + 0.2\text{N NaOH}$ , showed negative flow rates, which indicates no tendency to expansive reactivity. The solution containing  $\text{Ca}(\text{OH})_2 + 0.5\text{N NaOH}$  showed positive flow between 28 and 66 days, but the flow rate during this period was less than the 2.0-millimeter-per-day threshold rate indicated by the dashed line. Thus, although mildly expansive reactivity developed with this solution, it is not considered sufficiently severe to reflect a deleterious reaction.

Tests using the two solutions with 1N NaOH concentration produced sufficiently high flow rates to indicate deleterious reactivity. However, flow rates exceeded the threshold value only following initial 10- to 40-day periods during which rates were slightly below the threshold level.

Differences between the 1N NaOH solutions with and without  $\text{Ca}(\text{OH})_2$  were minor once the threshold rate was reached. However, this rate was initially reached at a test age of about 10 days without  $\text{Ca}(\text{OH})_2$  and about 40 days with  $\text{Ca}(\text{OH})_2$  in solution. Thus,  $\text{Ca}(\text{OH})_2$  served only to delay the time required to approach the flow rate for the 1N NaOH solution without  $\text{Ca}(\text{OH})_2$ .

Figure E2 summarizes results comparing flow rates for NaOH and NaOH + KOH solutions of equal normality and saturated with  $\text{Ca}(\text{OH})_2$ . The data show little or no significant difference in flow rate between corresponding solutions. For example, slopes of the curves for the 0.5N NaOH solution and the 0.25N NaOH + 0.25 KOH solutions are virtually identical

up to 40 days. For the one-normal solutions, straight NaOH solution produced a flow rate, after about 40 days, slightly greater than that for the NaOH + KOH solution. However, both solutions produced flow rates as high as the threshold rate. Thus, for this particular aggregate sample, similar conclusions are drawn for the NaOH and NaOH + KOH solutions with potential for alkali-silica reactivity. Whether this relationship would hold for other reactive materials is not known.

A summary of results for the NaOH and Na<sub>2</sub>SO<sub>4</sub> solutions, all saturated with Ca(OH)<sub>2</sub> is given on figure E3. Of particular interest is the difference in flow rate between the 1N NaOH and 1N Na<sub>2</sub>SO<sub>4</sub> solutions. The 1N NaOH solution produced a rate exceeding the threshold level, while the 1N Na<sub>2</sub>SO<sub>4</sub> solution produced essentially no flow. This clearly illustrates the dependence of alkali-silica reactivity on hydroxyl ion concentrations in solution, as opposed to sodium or potassium concentration. Low hydroxyl ion concentrations do not induce expansive reactivity, in spite of the high sodium concentrations within the range tested here. As long as anions other than hydroxyl ion electrically balance sodium or potassium ions in solution, deleterious reactivity should not occur.

Figure E4 shows the relationship between normality of the various solutions and differential flow at 66 days. As indicated, a straight line relationship exists between NaOH and NaOH + KOH normality and flow. This reflects the effect of increasing OH ion concentration as noted above. The plot also indicates that no flow occurred with Na<sub>2</sub>SO<sub>4</sub> regardless of sodium ion concentration within the range studied. Thus, sodium concentration, by itself, is not necessarily a measure of tendency to expansive reactivity in concrete.

## SUMMARY

This investigation of alkali-silica reactivity in four dams in the southeastern United States supplements a similar study of reactivity in five dams in the southwestern United States [8]. Beside obvious design differences in structures in the two studies, major differences and similarities exist that serve to provide a better overall picture of the development and manifestations of alkali-silica reactivity.

A major difference in the two studies is climatic exposure condition. Structures in southwestern United States are located in a warm to hot, dry to arid, desert region where atmospheric evaporation far exceeds precipitation. Thus, the long-term prevailing tendency in concrete is shrinkage due to drying. Southeastern United States is a warm to hot, generally humid, area where atmospheric precipitation exceeds evaporation. Thus, long-term tenden-

cies are to maintain relatively damp conditions in concrete in this area.

Another major difference in the structures that were studied in the two regions is the type of aggregate that has reacted. In structures in southwestern United States, the predominant reacted rock types were cryptocrystalline to glassy volcanic materials of andesitic to rhyolitic composition. In southeastern United States, the reacted rock types were chert and metamorphic rock types including quartzites and metagraywackes, schists, and gneisses. In all probability, the reactive component in these latter rock types was strained or poorly crystalline silica.

A third difference among structures in the two regions was alkali level of the cement. Except for the powerhouse at Parker Dam and a portion of Coolidge Dam where low alkali cement (less than 0.60 percent as equivalent sodium oxide) was reported to have been used, high-alkali cement apparently was used in all concrete, with alkali levels being generally higher for cement used in the southwestern structures.

Considering these differences, manifestations of distress due to alkali-silica reactivity were similar, but severity of cracking was generally greater in structures in southwestern United States. In all structures, the visual impression was gained that cracking due to reactivity was most severe in relatively shallow, unrestrained concrete members where concrete was not in direct contact with river water and where intermittent or prolonged drying could occur. This included roadways, walls, columns, piers, etc., in upper portions of the dams. Within these types of concrete members, cracking was generally more severe in structures in the arid southwestern region. In lower massive portions of the dams and in appurtenant structures that are in continual contact with water, cracking due to reactivity is practically nonexistent, and prominent cracks that extend downward from dry upper portions of structures to water level appear to terminate somewhat below water level.

The implications from these observations are that observed cracking is the net result of shrinkage due to surface drying and to internal expansion due to alkali-silica reactivity. Where drying can occur, expansion may not always be evident even though cracking is severe. In contrast, expansion may be significant but surface cracking may be negligible where drying does not occur and the concrete is in continual contact with water.

In relation to these observations, the two studies revealed that significant atmospheric drying occurred only to depths of several inches, even in structures located in the arid southwest region. At

slightly greater depths, relative humidities reached close to 100 percent, which is well above the 80- to 85-percent threshold level required to sustain expansive reactivity. In the wetter southeast region, a similar trend was found, except that surface drying was less pronounced in this region. These results indicate that, regardless of climatic exposure condition, sufficient mix water was retained in the concrete for long periods of time to sustain expansive reactivity.

Results from both studies further suggest that expansive reactivity can continue for years and that reduced rates of reaction most likely result from reduced amounts of available alkali. To a lesser extent, reduction and termination of expansive reactivity may result from lack of reactive aggregate as well. In any case, moisture would always appear to be sufficiently available to sustain expansive reactivity if the other requirements are met, even in warm and climatic regions.

Type of reactive aggregate appears to have played a significant role in rate of development of distress due to alkali-silica reactivity. Certain volcanic rock types of rhyolitic to andesitic composition appear to have reacted deleteriously much more rapidly than the cherts and metamorphic rock types in the southeastern structures. Severe cracking was reported within several years in the southwestern structures. In the southeastern structures, the reacted component appears to have been strained quartz, but the severity of distress resulting purely from reactivity is still somewhat debatable.

In the final analysis, it is evident from these two studies that rate and severity of alkali-silica reactivity varies with cement alkali level and type of reactive aggregate as would be anticipated. However, resulting distress is dependent on other circumstances as well. A predominant factor is restraint to movement, which is largely overlooked, but may be decisive in whether major cracking develops. Superimposed drying shrinkage may serve to accentuate such cracking. Damage due to alkali-silica reactivity thus must be considered in light of exposure conditions as well as the traditional factors of cement alkali levels and type of reactive rock type.

## BIBLIOGRAPHY

- [1] "Examination of Fontana Dam Concrete Cores," Corps of Engineers, U.S. Army Engineer Waterways Experiment Station, Petrographic Report, May 3, 1974.
- [2] Buck, Alan D., and Burkes, Jerry P., "Alkali-Silica Reaction in Concrete from Hiwassee Dam, North Carolina, Tennessee Valley Authority," Miscellaneous Paper C-78-10, U.S. Army Engineer Waterways Experiment Station, Final Report, August 1978.
- [3] Buck, Alan D., "Alkali-Silica Reaction in Concrete from the New Savannah Bluff Lock and Dam, Georgia-South Carolina, Miscellaneous Paper C-78-13, U.S. Army Engineer Waterways Experiment Station, Final Report, September 1978.
- [4] McDonald, James E., and Campbell, Roy L., "An Investigation of Concrete Condition, William Bacon Oliver Lock and Spillway," Appendixes D and F, Miscellaneous Paper C-77-5, U.S. Army Engineer Waterways Experiment Station, Final Report, June 1977.
- [5] Mather, Bryant, "Cracking of Concrete in the Tuscaloosa Lock," Highway Research Board Proceedings, pp. 218 to 233, December 1951.
- [6] Nilsson, Lars-Olof, "Moisture Effects on the Alkali-Silica Reaction," 6th International Conference, Alkalis in Concrete, Copenhagen, Denmark, pp. 201 to 208, 1983.
- [7] Krogh, Hanne, "Examination of Synthetic Alkali-Silica Gels," Alkali Aggregate Reactions Conference, Reykjavik, Iceland, pp. 131 to 163, 1975.
- [8] Stark, David, "Alkali-Silica Reactivity in Five Dams in Southwestern United States," REC-ERC-85-10, Bureau of Reclamation, Engineering and Research Center, 64 pp., July 1985.
- [9] Monfore, G. E., "A Small Probe-Type Gage for Measuring Relative Humidity," Portland Cement Association Research Department Bulletin 160, Skokie, Illinois, 1963.
- [10] Stark, David, "Osmotic Cell Test to Identify Potential for Alkali-Aggregate Reactivity," 6th International Conference, Alkalis in Concrete, Copenhagen, Denmark, pp. 351 to 357, 1983.





## **APPENDIX A**

### **FONTANA DAM\***

Fontana Dam is a concrete gravity structure built between 1942 and 1945. It is located on the Little Tennessee River in western North Carolina, about 50 miles south of Knoxville, Tennessee, and is operated as part of the Tennessee Valley Authority hydroelectric system. The dam is 480 feet high and 2,365 feet in length along the crest.

Coarse and fine aggregate for concrete were obtained from a quarry site about 1.2 miles downstream from the dam. This material is predominantly a metagraywacke with small amounts of schist or phyllite. The metagraywacke has also been described as quartzite. Three sources of cement were used in producing concrete. Alkali contents reported for these cements ranged up to 0.71 and 0.75 percent as equivalent sodium oxide for two of the cements, and averaged 0.64 percent for the third cement.

---

\* This appendix is an edited version of a report by Construction Technology Laboratories, Inc.

Field observations in the present study revealed prominent map cracking in the roadway at the top of the dam, with numerous cracks being open while others were filled with secondary reaction products. In contrast, at ground level near the adit at elevation 1315 abnormal map cracking was faint to non-existent. Inside the adits at elevation 1315 and elevation 1700, there was no visible map cracking or, for that matter, no cracking observed whatsoever.

Of major concern regarding Fontana Dam is the development of a large inclined fracture in upper levels of the structure near the curve in the left abutment. Presently, concrete on the two sides of the fracture is post-tensioned together roughly normal to the plane of the fracture, but it is not known whether reactivity caused or contributed to the initial formation of the fracture, or to growth in height of the dam.

In this study, sample sites were selected to include the range of conditions noted above.



Sample	Location	Depth (in)	Relative humidity* (%)
F1	Sample taken 9 ft upstream from center lg. joint, at El. 1315, east wall of gallery, 46 in. above floor level. No map cracking or other evidence of alkali-silica reactivity was observed.	1/2 to 1	100
		2 to 2-1/2	98
		4 to 4-1/2	100
		8 to 8-1/2	95
		16 to 16-1/2	100
		24 to 24-1/2	97
F2	Sample taken in Block 34, in adit at El. 1700 north wall (end) of gallery, 10 ft from joint between Blocks 33 and 34, 24 in. above floor. No map cracking or other evidence of alkali-silica.	1/2 to 1	55
		2 to 2-1/2	54
		4 to 4-1/2	85
		8 to 8-1/2	82
		16 to 16-1/2	92
		24 to 24-1/2	100
F3	Sample taken in Block 35, in roadway at top of dam, El. 1727, 4 ft from curb, westbound lane, 7 ft from joint. Prominent map cracking was observed.	1/2 to 1	97
		2 to 2-1/2	100

\* Relative humidity referenced to 70 to 75 °F.

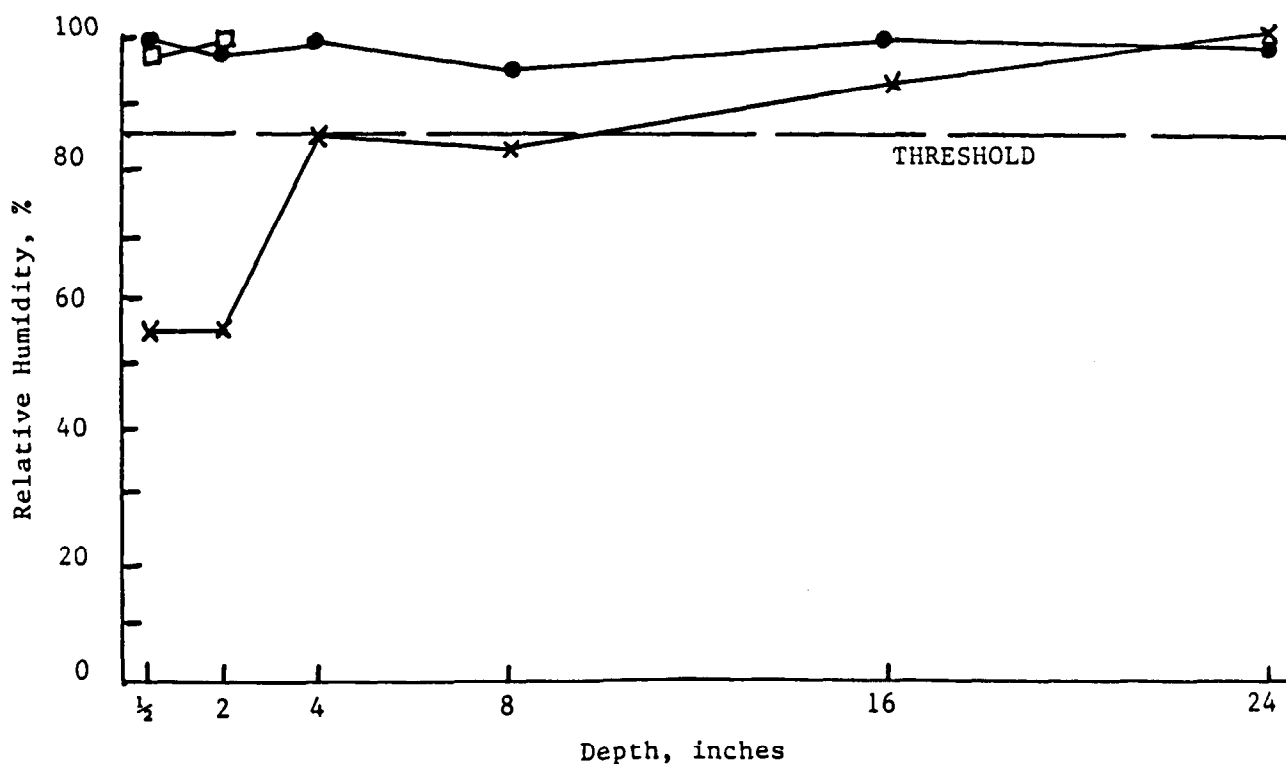


Figure A1. — Relative humidity data for Fontana Dam Concrete.

Table A1. — Results of petrographic examination of cores from Fontana Dam.

Core No.	Core location, surface condition of concrete	Depth examined (in)	Observations
1	Core taken horizontally into north (end) wall of adit at El. 1700, Block 34, 24 in. above floor. No cracking was observed.	0 to 9	Coarse aggregate was a crushed metagraywacke consisting mainly of quartz and feldspar with lesser biotite, which shows preferred orientation. Maximum particle size is 1-1/2 in. The fine aggregate is crushed material of the same rock types, and consists primarily of quartz, feldspar, and biotite mineral grains. The core did not display abnormal microcracking. One fine microcrack extends to the finished surface from a depth of about 1/2 inch in the core and appears to be due to drying shrinkage. The metagraywacke particles show no evidence of expansive reactivity. These particles failed to display reaction rims, internal alteration, or associated microcrack patterns characteristic of reactivity. A few dark schist particles display faint, discontinuous, rims but there was no evidence of associated cracking, internal alteration of the particles, or gel deposits. The few isolated microcracks in particles are considered to have been present prior to mixing in the concrete. The concrete is non-air entrained. Ettringite lines some entrapped air voids. There was no evidence of any form of progressive deterioration.
		22 to 28	Coarse and fine aggregate are the same as above. Dark reaction rims were observed on numerous metagraywacke and dark schistose particles in the coarse and fine aggregate. A few tight microcracks extend along the interface between rimmed aggregate particles and the mortar. Microcracking in the mortar is more extensive in this core than in the core section from the 0- to 9-in. depth. However there were no alkali-silica gel deposits observed nor microcracks in the mortar that indicate expansion. The concrete is nonair entrained. Ettringite lines many entrapped air voids. There is no evidence of progressive deterioration.
4	Core taken horizontally into east wall of adit at El. 1315, 9 ft upstream from lg. jt, 46 in. above floor. No cracking was evident.	6 to 14	Coarse aggregate is a crushed metagraywacke grading into minor proportions of schist. Major components are quartz and feldspar with lesser proportions of biotite. Maximum particle size is 1-1/2 in. The fine aggregate is crushed material of the same rock and mineral composition as the coarse aggregate. Most metagraywacke particles display reaction rims characteristic of alkali-silica reactivity. Internal microcracking occurs in numerous particles but none of the cracks extend into surrounding mortar. Alkali-silica gel deposits are of very minor occurrence but were found, together with ettringite and calcite, to line entrapped air voids. The concrete is nonair entrained. There were no other forms of progressive deterioration noted.
6A	Core was taken in roadway at top of dam, Block 35, 6 ft from sidewalk. Prominent map cracking was present.	6 to 14	Coarse aggregate is a crushed metagraywacke grading into schist, which is present in minor proportion. Major components are quartz and feldspar with lesser amounts of biotite. Maximum particle size is 1 in. The fine aggregate is crushed material of the same composition of rock and mineral types as the coarse aggregate. Coarse and fine rock particles display well-defined, dark, reaction rims. Abnormal microcracking extends transversely across the core. Microcracks that appear to originate within rimmed particles extend into surrounding mortar, thus indicating abnormal expansion. Extensive deposits of alkali-silica gel occur in microcracks, in entrapped air voids, and within aggregate particles along visible rims, in aggregate sockets, and in microcracks within particles. The collective evidence indicates severe alkali-silica reactivity with attendant cracking and expansion has occurred. Ettringite and calcite are commonly found with alkali-silica gel in entrapped air voids. The concrete is nonair entrained. There is no evidence of other forms of progressive cracking.

Table A2. — Length change of Fontana Dam cores stored over water or in water or 1N NaOH solution at 100 °F.

Core No.	Location	Depth (in)	Exposure	Percent length change at age indicated					
				1 mo.	2 mos.	3 mos.	4 mos.	6 mos.	7 mos.
F1A	North (end wall of adit at El. 1700. Block 34, 72 in. above floor. No cracking.	12 to 18	In H <sub>2</sub> O	0.050	0.040	0.038	0.040	0.046	0.048
F1B		21 to 27	In NaOH	.044	.050	.054	.068	.080	.088
F2A			Over H <sub>2</sub> O	.026	.026	.034	.034	.028	.028
F3B	East wall of adit at El. 1315, 9 ft upstream from lg. joint, 46 in. above floor. No cracking.	24 to 30	In NaOH	.048	.056	.064	.074	.084	.090
F5A	In roadway, top of dam, Block 35, 6 to 8 ft from sidewalk. Prominent map cracking.	24 to 30	In NaOH	.066	.082	.090	.096	.122	.132
F6A		23 to 29	In Na <sub>2</sub> O	.046	.048	.048	.054	.058	.064
F6AA		24 to 30	Over H <sub>2</sub> O	.042	.050	.058	.060	.056	.052

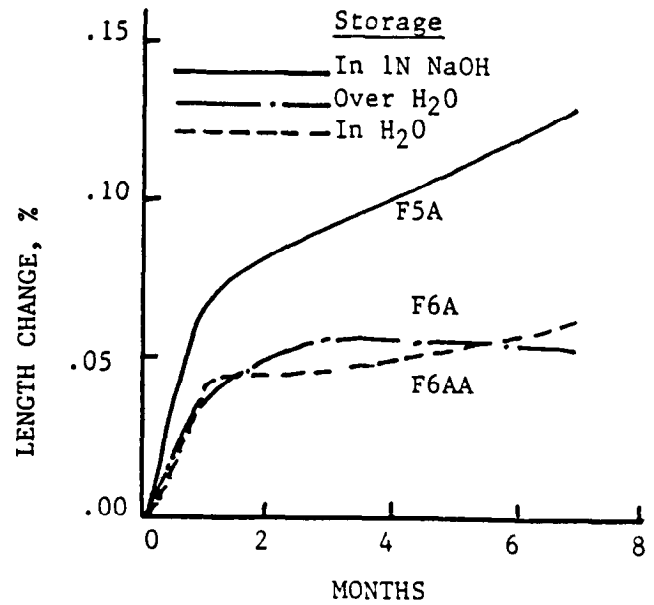
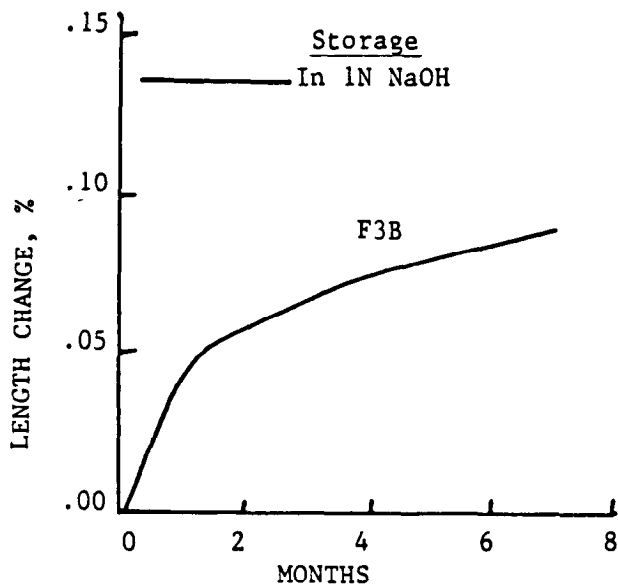
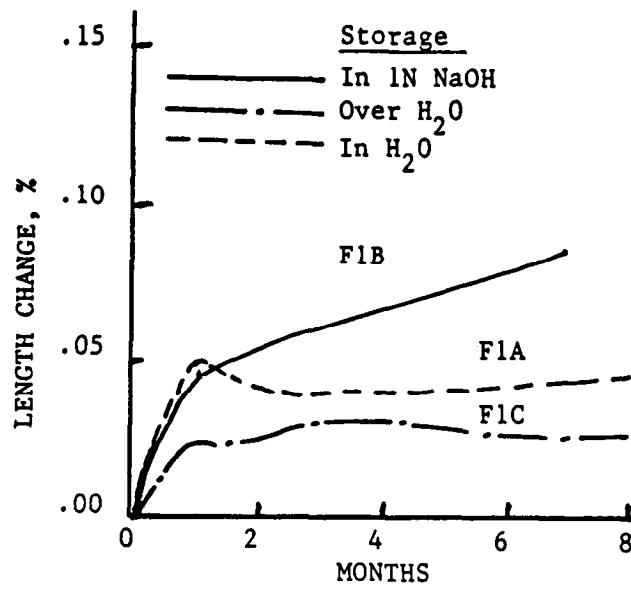


Figure A2. — Length change of cores stored under various conditions.

## **APPENDIX B**

### **HIWASSEE DAM\***

Hiwassee Dam, which is operated by the Tennessee Valley Authority, is located on the Hiwassee River in western North Carolina, about 60 miles south of Knoxville, Tennessee. It was built between 1936 and 1940 and is a straight concrete gravity structure, 307 feet high and 1,376 feet long at its crest.

Coarse aggregate for the structure was a locally derived, crushed, metagraywacke, also labeled micaceous quartzite. Six-inch maximum size aggregate was utilized. The fine aggregate was crushed material derived from the same native rock. A low-heat cement was used for making concrete, but its alkali content is not known.

The initial investigation to determine whether alkali-silica reactivity had developed was made in 1978. From that study, it was concluded that alkali-silica reactivity could be responsible for the observed cracking.

In this investigation, abnormal map cracking was observed at various locations in the dam structure. Prominent large-scale map cracking was observed in the roadway and wall along the roadway at the top of the dam. Here, numerous cracks were open while less prominent, tighter, cracks were often filled with a white secondary reaction product. At lower elevations, such as at levels near the powerhouse, abnormal map cracking was faint or not visible. Sample locations for this study included these conditions.

---

\* By Construction Technology Laboratories, Inc.





Sample	Location	Depth (in)	Relative humidity* (%)
H1 ●	Sample taken in Block 16, in roadway at top of dam, Northwest bound traffic lane. Large-scale map cracking was present.	1/2 to 1	95
		2 to 2-1/2	95
		4 to 4-1/2	94
		8 to 8-1/2	98
H2 ×	Sample taken in concrete wall along roadway at south end of dam. Wall 15 in. thick at sample location. Sample taken 20 in. down from top at wall. Open map cracking was present.	1/2 to 1	92
		2 to 2-1/2	91
		4 to 4-1/2	95
		7 to 7-1/2	94
H3 □	Sample taken into downstream face of dam, in Block 16, side of doorway of adit at El. 1312. Faint map cracking was present.	1/2 to 1	84
		2 to 2-1/2	90
		4 to 4-1/2	88
		8 to 8-1/2	87
		16 to 16-1/2	88
		24 to 24-1/2	98

\* Relative humidity referenced to 70 to 75 °F.

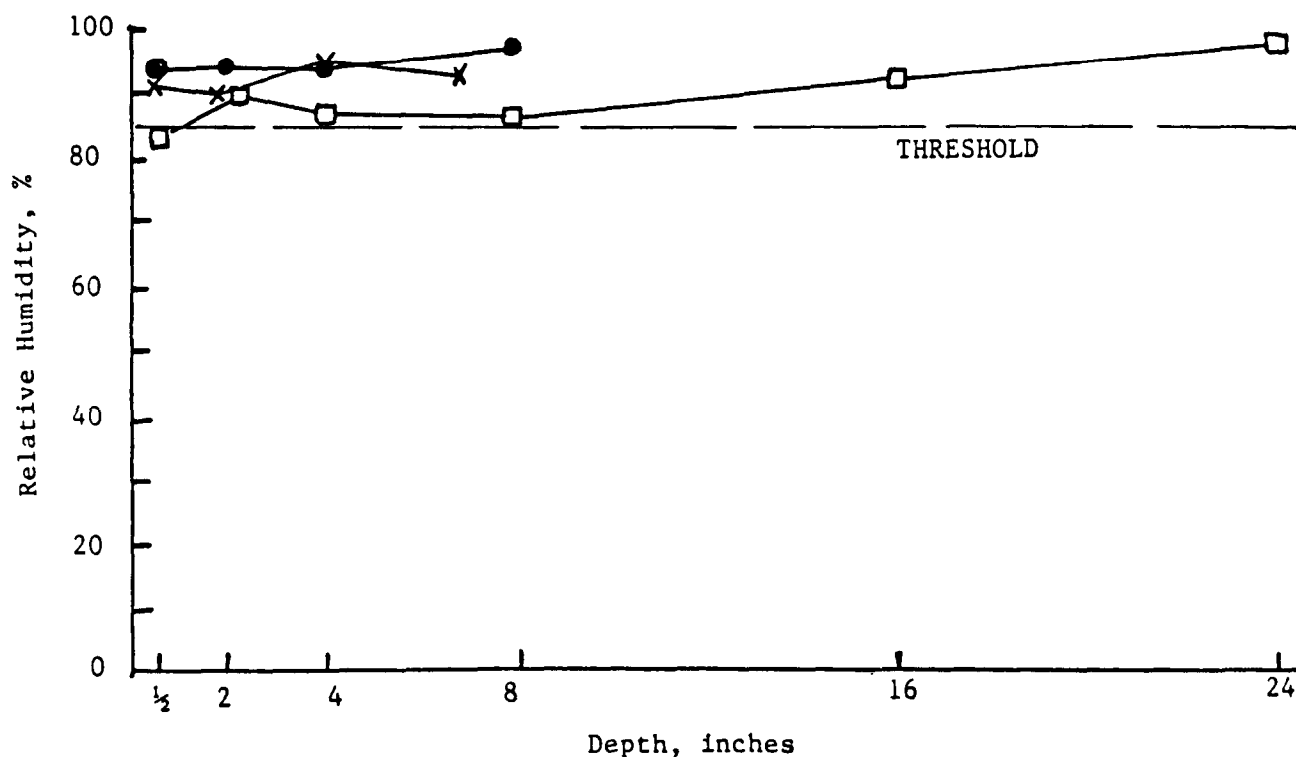


Figure B1. — Relative humidity data for Hiwassee Dam concrete.

Table B1. — Results of petrographic examination of cores from Hiwassee Dam.

Core No.	Core location, surface condition of concrete	Depth examined (in)	Observations
7	Core taken vertically into roadway in Block 17, southbound traffic lane. Area displays large-scale map cracking.	10-18	Coarse aggregate is almost entirely crushed metagraywacke grading into schist. They consist of quartz and feldspar with about 10 to 50% biotite and muscovite. Most particles show some fine layering with preferred orientation of mica. The fine aggregate is composed of rock and mineral types present in the coarse aggregate. Maximum particle size is 1-3/4 in. The core contains numerous microcracks which are lined with alkali-silica gel. These cracks extend transversely across the core; some extend from coarse aggregate particles into surrounding mortar. Aggregate sockets and fractures within coarse aggregate particles reveal localized or spotty deposits of alkali-silica gel associated with quartz and feldspar. Virtually all coarse aggregate particles, and coarser fine aggregate particles, display well-defined, dark, reaction rims, regardless of color and texture. Evidence strongly indicates that alkali-silica reactivity has caused abnormal cracking and expansion in the concrete. There was no evidence of other forms of progressive deterioration. The concrete is nonair entrained.
10	Core taken near door of adit at El. 1312, 4 ft above floor. Concrete displays faint map cracking.	19-28	Coarse aggregate is crushed and consists almost entirely of metagraywacke to schist containing quartz and feldspar with varying quantities of biotite and muscovite ranging up to about 50% of the rock. Some preferred orientation of mica is evident. Maximum particle size is 1-1/4 in. The fine aggregate is composed of the same rocks and minerals as are found in the coarse aggregate. The core contains only a few localized microcracks in the mortar. A few isolated microcracks also are present in aggregate particles. They may or may have been in the aggregate when the concrete was placed. Essentially all coarse and coarser fine aggregate particles display reaction rims, with the rim being barely visible in the dark, biotite-rich particles. Examination of freshly fractured surfaces and aggregate sockets failed to reveal the presence of alkali-silica gel. Gel was found only in several entrapped air voids. There was no evidence of any form of progressive deterioration. The concrete is nonair entrained.

Table B2. — Length change of Hiwassee Dam cores stored over water or in water or 1N NaOH solution at 100 °F.

Core No.	Location	Depth (in)	Exposure	Percent length change at age indicated					
				1 mo.	2 mos.	3 mos.	4 mos.	6 mos.	7 mos.
H7A	Cores taken vertically into roadway at top of dam, Block 17, south-bound lane. Area displays large-scale map cracking.	24 to 30	In NaOH	0.040	0.044	0.046	0.052	0.056	0.062
H8A		15 to 21	Over H <sub>2</sub> O	.040	.036	.038	.038	.036	.034
H8B		21 to 27	In H <sub>2</sub> O	.048	.046	.052	.052	.052	.056
H9A	Core taken near outside door of adit at El. 1312, 4 ft above floor. Concrete displays faint map cracking.	17 to 23	In NaOH	.044	.052	.058	.060	.064	.076
H9B		18 to 24	In H <sub>2</sub> O	.018	.016	.010	.012	.010	.012
H9C		31 to 37	Over H <sub>2</sub> O	.048	.048	.048	.048	.040	.044

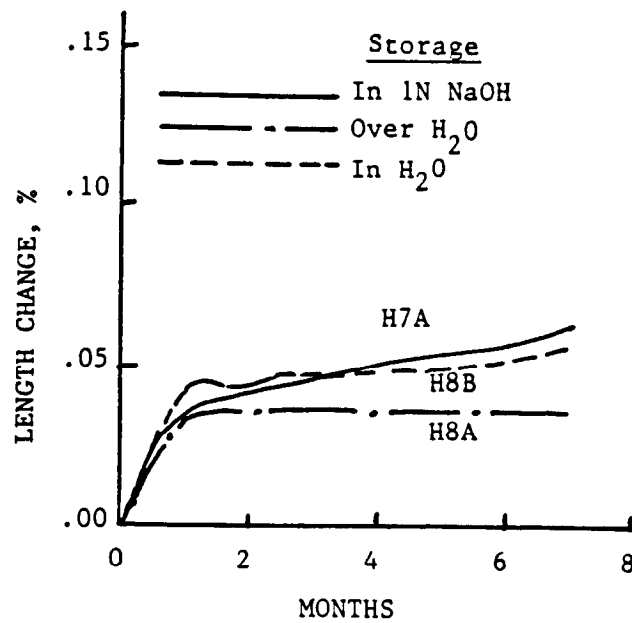
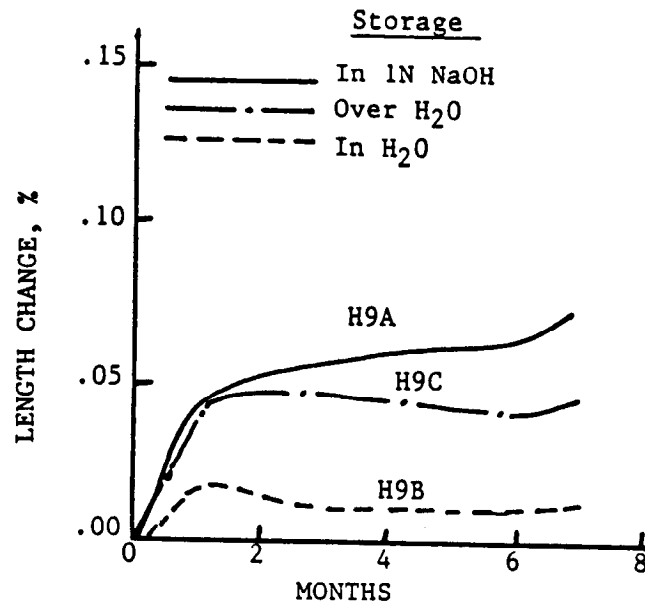


Figure B2. — Length change of cores stored under various conditions, Hiwassee Dam.



## **APPENDIX C**

### **NEW SAVANNAH BLUFF LOCK AND DAM\***

New Savannah Bluff Lock and Dam was built in 1937, and is located on the Savannah River several miles south of Augusta, Georgia, on the Georgia-South Carolina border. Crushed granite gneiss and natural quartzite gravel were used as coarse aggregate, while a natural quartz sand was used as fine aggregate. The alkali content of the cement, obtained from two sources, is not known.

The age of the structure when abnormal, large scale, map cracking was first reported is not known. However, a 1973 Corps of Engineer investigation concluded that alkali-silica reactivity had not developed. An investigation of cracking in other structures in Georgia in the 1970's disclosed that a granite gneiss from the same source as that used in the New Savannah Bluff Lock and Dam, or one similar to it, was associated with reactivity. In a later

1970's study, it is indicated that the granite gneiss appeared to have reacted deleteriously in the lock and dam, with the quartzite gravel also possibly having reacted.

In the present investigation, severity of map cracking was observed to vary in the structure. Prominent large-scale map cracking was observed on the south face of the abutment on the South Carolina side of the dam. Open cracks as well as cracks partially filled with white secondary reaction products were observed. Prominent horizontal cracks, together with map cracking, were observed in the abutment wall which extends downstream from the abutment on the South Carolina side.

Cracking was less severe in the top surface of the lock walls and in the upper levels of the piers, which are well above water level. Concrete in continuous contact with river water revealed no evidence of abnormal cracking.

---

\* By Construction Technology Laboratories, Inc.



Sample	Location	Depth (in)	Relative humidity* (%)
S1	Sample taken from south face of abutment, South Carolina side, 24 in. from upstream face and 40 in. up from floor of landing. Large-scale map cracking present with dark deposits in tighter cracks.	1/2 to 1	97
		2 to 2-1/2	93
		4 to 4-1/2	95
		8 to 8-1/2	96
		16 to 16-1/2	100
		24 to 24-1/2	100
S2	Sample taken from south face of abutment, South Carolina side, 90 in. from upstream face of landing and 42 in. up from floor of landing. Map cracking moderate and less severe than at S1.	1/2 to 1	90
		2 to 2-1/2	96
		4 to 4-1/2	96
		8 to 8-1/2	96
		16 to 16-1/2	95
		24 to 24-1/2	96
S3	Sample taken from south face of abutment wall, South Carolina side 15-1/2 ft below top of wall, 19 ft downstream from abutment. Prominent horizontal crack and open map cracks. Some map cracking with deposits.	1/2 to 1	91
		2 to 2-1/2	100
		4 to 4-1/2	100
		8 to 8-1/2	98
		12 to 12-1/2	100

\* Relative humidity referenced to 70 to 75 °F.

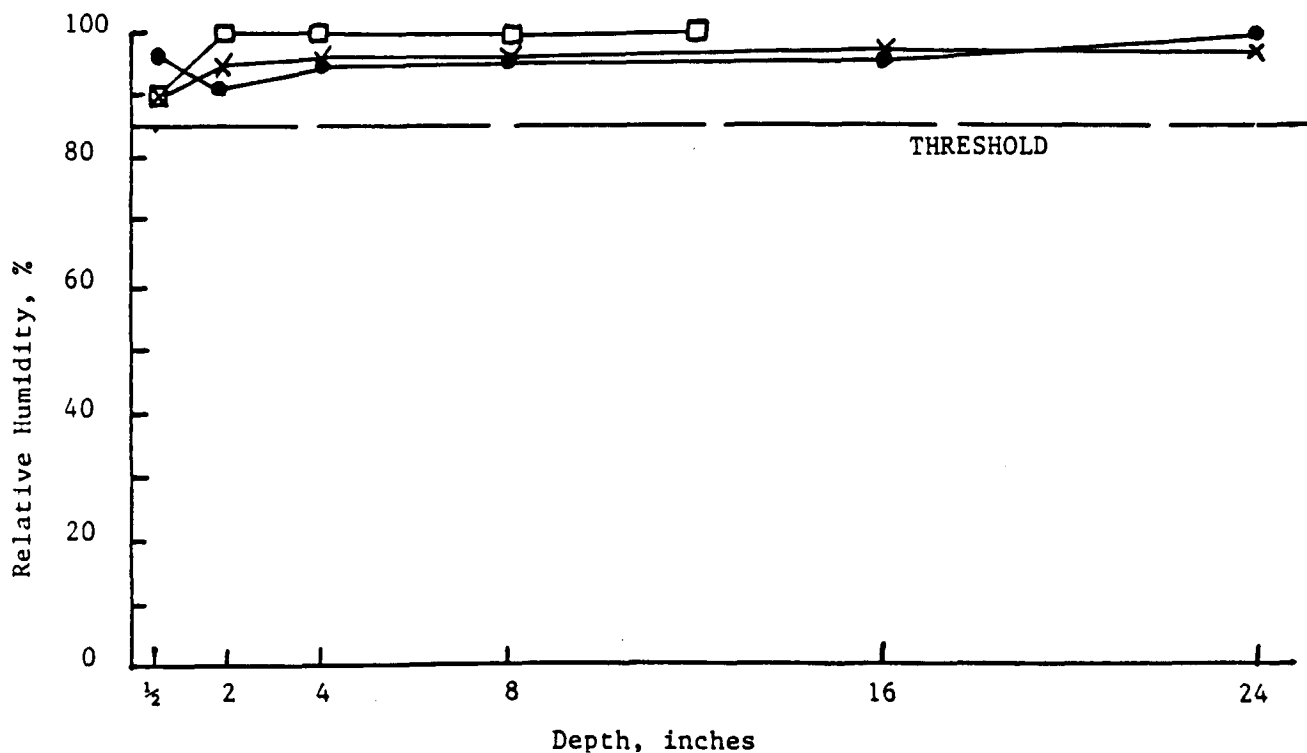


Figure C1. — Relative humidity data for New Savannah Bluff Lock and Dam.

Sample	Location	Depth (in)	Relative humidity* (%)
S4	Sample taken from top of first pier from lockmaster's house, ● 4 ft from north face of pier, 4 ft from west face of pier. Aluminum paint on surface. Map cracking present in top surface.	1/2 to 1	90
		2 to 2-1/2	100
		4 to 4-1/2	100
		8 to 8-1/2	100
		16 to 16-1/2	100
S5	Sample taken from top surface of lock wall on landside, □ 18 ft west of gate, 12 ft from face of lock wall. Well-defined map cracking is present.	1/2 to 1	95
		2 to 2-1/2	95
		4 to 4-1/2	97
		8 to 8-1/2	98
		16 to 16-1/2	99
		24 to 24-1/2	100

\* Relative humidity referenced to 70 to 75 °F.

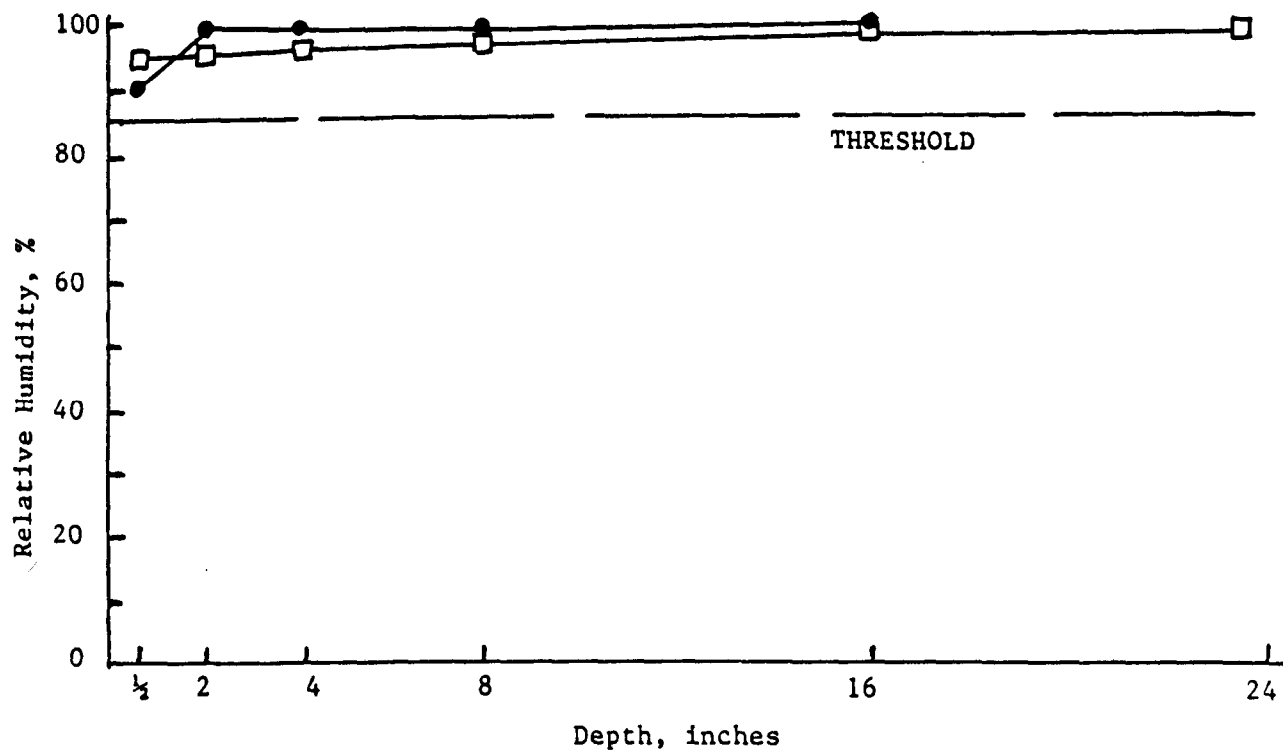


Figure C2. — Relative humidity data for New Savannah Bluff Lock and Dam, samples No. S4 and S5.



Table C1. — Results of petrographic examination of cores from New Savannah Bluff Lock and Dam.

Core No.	Core location, surface condition of concrete	Depth examined (in)	Observations
1A	Core taken from top surface of lock wall on landside, 18 ft from west of gate, 12 ft from face of lock wall. Well-defined map cracking is present.	19-23	Coarse aggregate consists of an estimated 35 to 50% crushed granite gneiss and 50 to 65% quartzite gravel particles. Maximum particle size was 3/4 in. The fine aggregate consists almost entirely of quartz with traces of chert. The granite gneiss particles failed to display any evidence of alkali reactivity, as indicated by reaction rims, microcracks extending from these particles into surrounding mortar, and internal alteration of the particles. Several quartzite particles displayed reaction rims believed to have formed by reaction in the concrete. However, there were no associated microcracks visible or gel reaction products present. Entrapped air voids and some coarse aggregate sockets contained ettringite deposits. The concrete is nonair entrained. There is no evidence of progressive forms of deterioration.
2	Core taken from south face of abutment on South Carolina side, 2 ft from upstream face, and about 3 ft up from landing. Large scale map cracking is present, with dark deposits present in tighter cracks.	0-9	Coarse aggregate consists of about 50% crushed granite gneiss and about 50% quartzite gravel. Maximum particle size is about 1 in. The fine aggregate consists entirely of quartz, with traces of chert. Several gneiss particles display thin, partial reaction rims. However, none displayed abnormal internal microcracks or alteration. Numerous quartzite particles displayed rims, some of which appeared to be previous weathering rims, while other, very dense, rims appeared to have formed in the concrete. Alkali-silica gel reaction products were found to be associated only with quartzite coarse aggregate particles. These products occurred in few entrapped air voids, along paste-quartzite aggregate interfaces, and between quartz grains within several quartzite particles. The concrete is nonair entrained. Secondary ettringite was found as linings in some entrapped air voids. There was no evidence of other forms of progressive deterioration.
6	Core taken from top of first pier from lock-master's house, 4 ft from north face of pier, 4 ft from west face. Aluminum paint on surface. Map cracking was present on surface.	0-10	The coarse aggregate consists of about 60 to 75% crushed granite gneiss and 25 to 40% quartzite gravel. Maximum particle size is 1-1/8 in. The core contains a vertical crack which extends from the exposed surface to a depth of 1-5/8 in breaks aggregate, and terminates at the periphery of a gneiss aggregate particle. The socket of this particle, as well as the surface of the crack, contain thin layers of alkali-silica gel and calcium carbonate. Numerous deposits of alkali-silica gel also occur in entrapped air voids and adjacent to quartzite and a few gneiss particles throughout the core. However, there is a conspicuous absence of microcracking in the core. Deposits of secondary ettringite and calcium carbonate frequently occur in entrapped air voids. The concrete is non-air entrained. There is no other evidence of progressive deterioration.

Table C2. — Length change of New Savannah Bluff Lock and Dam cores stored over water or in water or 1N NaOH solution at 100 °F.

Core No.	Location	Depth (in)	Exposure	Percent length change at age indicated					
				1 mo.	2 mos.	3 mos.	4 mos.	6 mos.	7 mos.
1A	Cores taken from top surface of lock wall on landside, 18 ft west of gate, 12 ft from face of wall.	5-11	In H <sub>2</sub> O	0.026	0.024	0.014	0.024	0.024	0.030
1B		13-19	In NaOH	.046	.032	.026	.038	.038	.038
2B	Cores taken from south face of abutment, South Carolina side, 2 ft and 8 ft from upstream face 3 to 4 ft up from floor.	12-18	In NaOH	.032	.036	.032	.038	.034	.042
3B		12-18	In H <sub>2</sub> O	.028	.030	.016	.032	.032	.036
4B	Cores taken from south face of south abutment wall, 15 ft from top of wall, 20 ft downstream from abutment.	12-18	In NaOH	.030	.024	.022	.028	.028	.038
5B	Cores taken from top surface	12-18	In NaOH	.030	.024	.024	.028	.030	.030
5C	of first pier from lockmaster's	12-18	In H <sub>2</sub> O	.022	.020	.020	.018	.018	.014
6B	house, 4 ft from faces of pier.	5-11	Over H <sub>2</sub> O	.028	.026	.014	.032	.032	.036

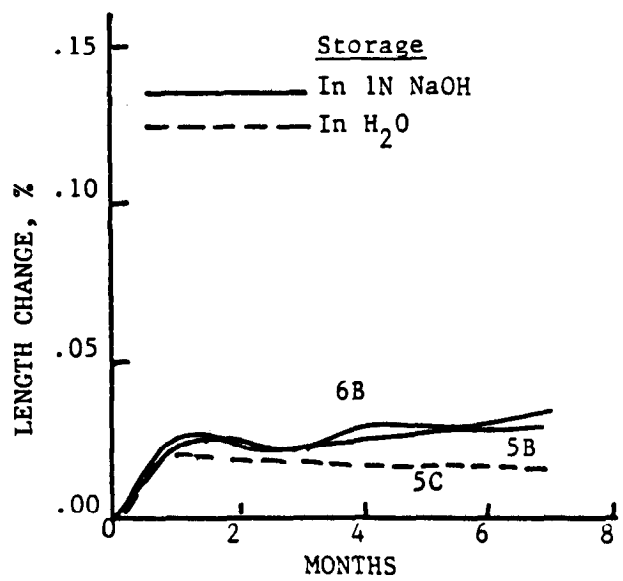
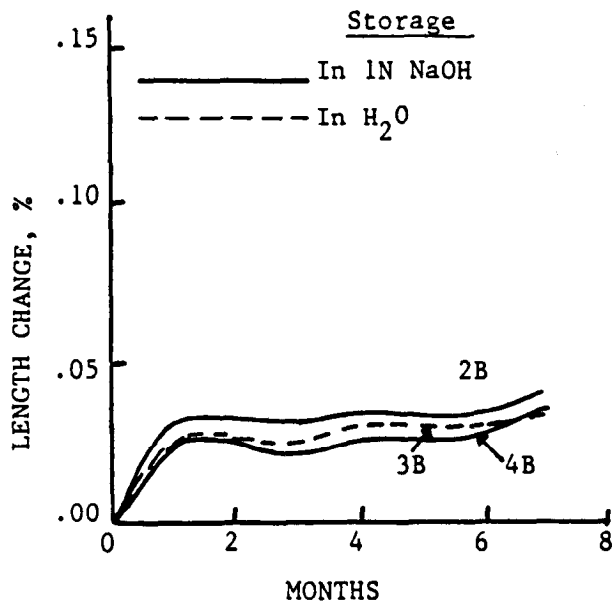
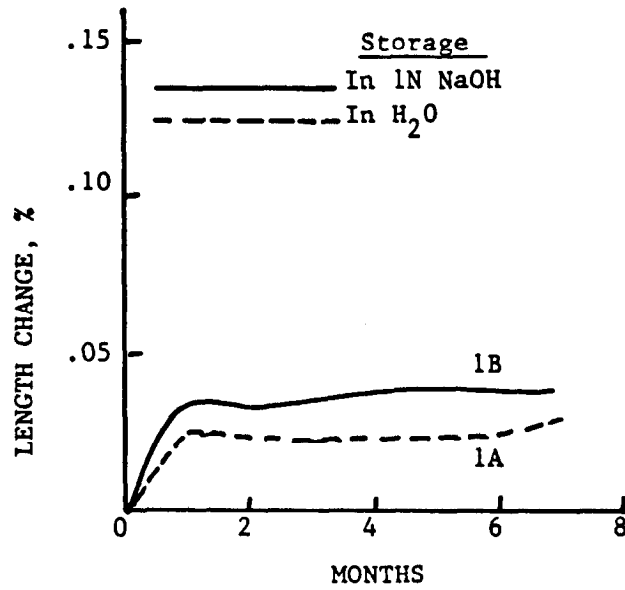


Figure C3. — Length change of cores stored under various conditions, New Savannah Bluff Lock and Dam.



## **APPENDIX D**

### **OLIVER LOCK AND SPILLWAY\***

Oliver Lock and Spillway, formerly known as Tuscaloosa Lock and Dam, is located on the Warrior River near Tuscaloosa, Alabama. It was built between 1937 and 1939. Portland cement for this installation was supplied from two mills; the alkali contents of these cements are not known but are believed to be high. Coarse and fine aggregates were supplied from Gulf coastal area sands and gravels. They are nearly 100% siliceous materials, with the coarse aggregate consisting of 40 to 50% chalcedonic chert, 50 to 60% quartzite, sandstone, and quartz, and traces of other materials. The fine aggregate is predominantly quartz with minor amounts of feldspar and other materials. Chert was common in the coarse sand sizes.

About 8 years after construction, abnormal cracking was reported in lock walls with more severe cracking being associated with the use of one of the two cements. Examination of concrete cores then

revealed that severe alkali-silica reactivity involving chalcedonic chert had caused expansion and cracking, regardless of source of cement. Also, it was established that cracking was largely restricted to concrete near exposed surfaces. However, evidence of reactivity in a 60-foot-long vertical concrete core was manifested as gel deposits and reaction rims in aggregate particles through the full length of the core. Fifty-six-day expansions of cores, taken in 1976 by the Corps of Engineers and stored over water in sealed containers at 100 °F, reached between 0.11 and 0.28 percent, depending on location of the core in the lock wall.

In this investigation, the most severe cracking was observed in the second monolith from the upstream end of the landside lock wall. Less severe map cracking was observed in other monoliths in the lock from which concrete cores were taken for the present investigation. Due to drilling difficulties, only relatively short cores were obtained from the riverside lock wall. Samples for relative humidity measurements were obtained from three locations.

---

\* By Construction Technology Laboratories, Inc.



Sample	Location	Depth (in)	Relative humidity* (%)
01	Sample taken at top of second block from upstream end of landslide lock wall, 11 ft from first joint and 14 ft from inside surface of wall. Worst condition block in wall. Severe large-scale map cracking is present, with 1-1/2-in. uplift of top surface relative to adjacent block.	1/2 to 1	82
		2 to 2-1/2	94
		4 to 4-1/2	99
		8 to 8-1/2	100
02	Sample taken in landside lock wall, in third block from upstream end, 10 ft below top of wall at bottom of stairway to landing. Map cracking moderate on top surface of block, none visible on vertical surface from which core was taken.	1/2 to 1	82
		2 to 2-1/2	82
		4 to 4-1/2	73
		8 to 8-1/2	75
03	Sample taken vertically from top surface of lock wall on river-side, 297 ft downstream from lockmaster's house, 4 ft from riverside wall, 8 ft from nearest joint. Area sampled is example of relatively good concrete. Only few map cracks visible.	1/2 to 1	80
		2 to 2-1/2	98
		4 to 4-1/2	96
		8 to 8-1/2	99
		16 to 16-1/2	99

\* Relative humidity referenced to 70 to 75 °F.

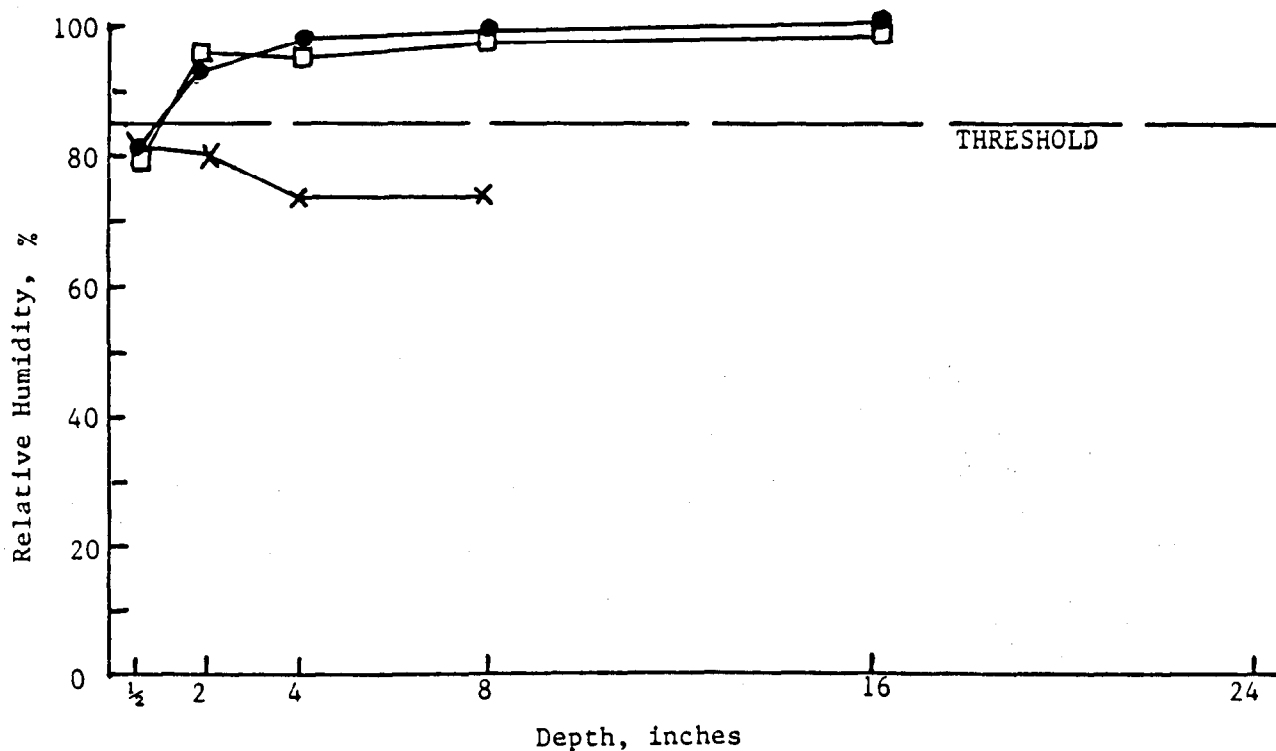


Figure D1. — Relative humidity data for Oliver Lock and Spillway concrete.

Table D1. — Results of petrographic examination of cores from Oliver Lock and Spillway.

Core No.	Core location, surface condition of concrete	Depth examined (in)	Observations
B	Core taken horizontally into landside wall of lock, at stairway and landing in third block from upstream end.	14–19	Coarse consists of about 35 to 50% chert and 50 to 65% quartzite, sandstone, and quartz. The fine aggregate consists of 80 to 90% quartz, with 10 to 20% quartzite, chert, and feldspar. Reaction rims occur on most chert particles and on a new sandstone and quartzite particles. Alkali-silica gel is present in most reacted chert particles into surrounding mortar. Copious amounts of gel are also present in entrapped air voids and in aggregate sockets. Observations indicate that severe alkali-silica reactivity has developed which has caused extensive cracking in the concrete. There is no evidence of other forms of progressive deterioration.
C	Core taken vertically into riverside lock wall, about 300 ft south of lockmaster's house, 4 ft from riverside edge. Area displays a few map cracks but concrete is in relatively good condition.	0–5-½	Coarse aggregate consists of about 35 to 50% chert, with the remainder being quartzite, sandstone, and quartz. The fine aggregate consists primarily of quartz with lesser amounts of chert and traces of feldspar. There was no abnormal cracking in the paste matrix of the concrete. Dense, reaction rims were observed on numerous chert and a few sandstone particles. None of these cracks were found to extend into surrounding mortar. Examination of fractured surfaces revealed evidence of numerous deposits of alkali-silica gel which typically occurred in entrapped air voids. No gel was found in microcracks within reacted particles. The observations indicate that reactivity in this core produced significant amounts of reaction product but resulted in no localized microcracking. The concrete is nonair entrained. There is no evidence of other forms of progressive deterioration.

Table D2. — Length change of Oliver Lock and Spillway Cores stored over water or in water or 1N NaOH solution at 100 °F.

Core No.	Location	Depth (in)	Exposure	Percent length change at age indicated					
				1 mo.	2 mos.	3 mos.	4 mos.	6 mos.	7 mos.
A	Cores taken horizontally into south face of landside	11 to 17	In NaOH	0.050	0.050	0.050	0.054	0.052	0.058
AA	lock wall, at landing of stairway. Map cracking present on top surface of wall, none on south face.	4 to 10	In H <sub>2</sub> O	.040	.044	.040	.042	.044	.050
C		12 to 18	Over H <sub>2</sub> O	.020	.020	.024	.024	.018	.024
CC		12 to 18	In NaOH	.028	.026	.026	.026	.030	.030



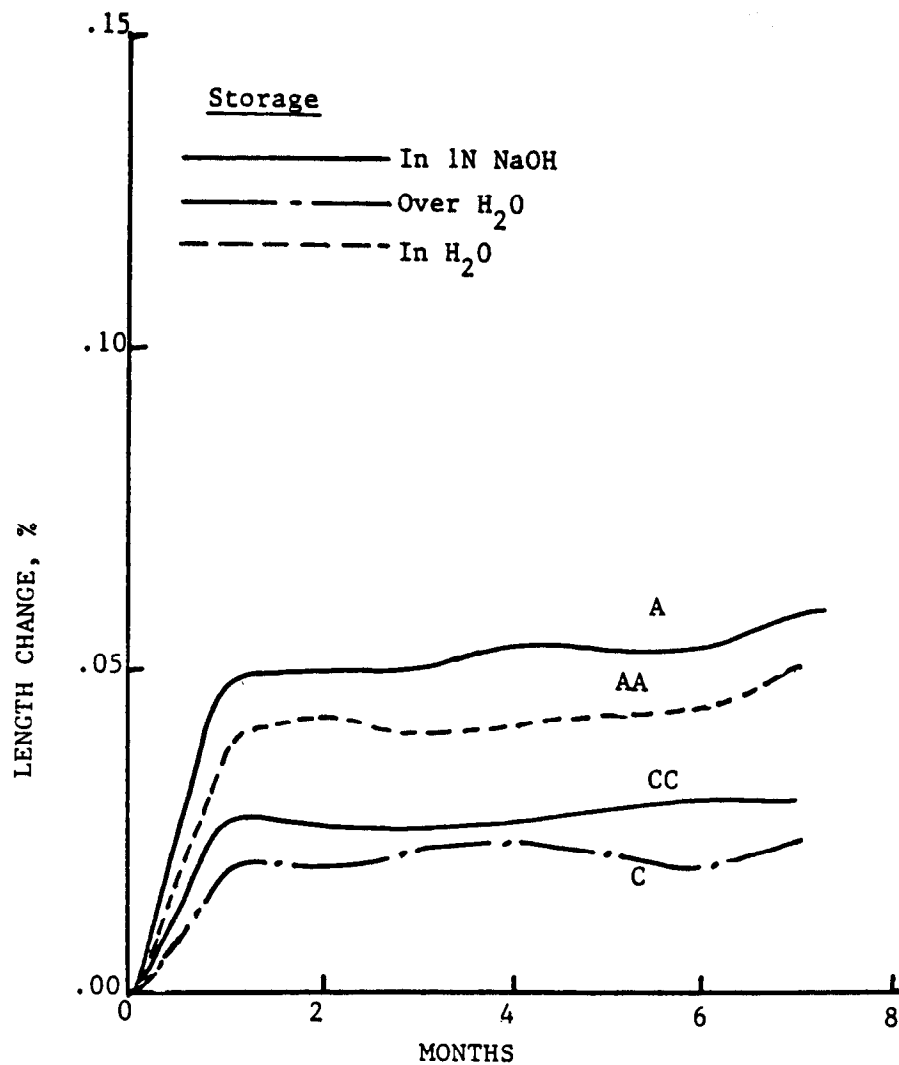


Figure D2. — Length change of cores stored under various conditions, Oliver Lock and Spillway.



**APPENDIX E**  
**OSMOTIC CELL DATA**



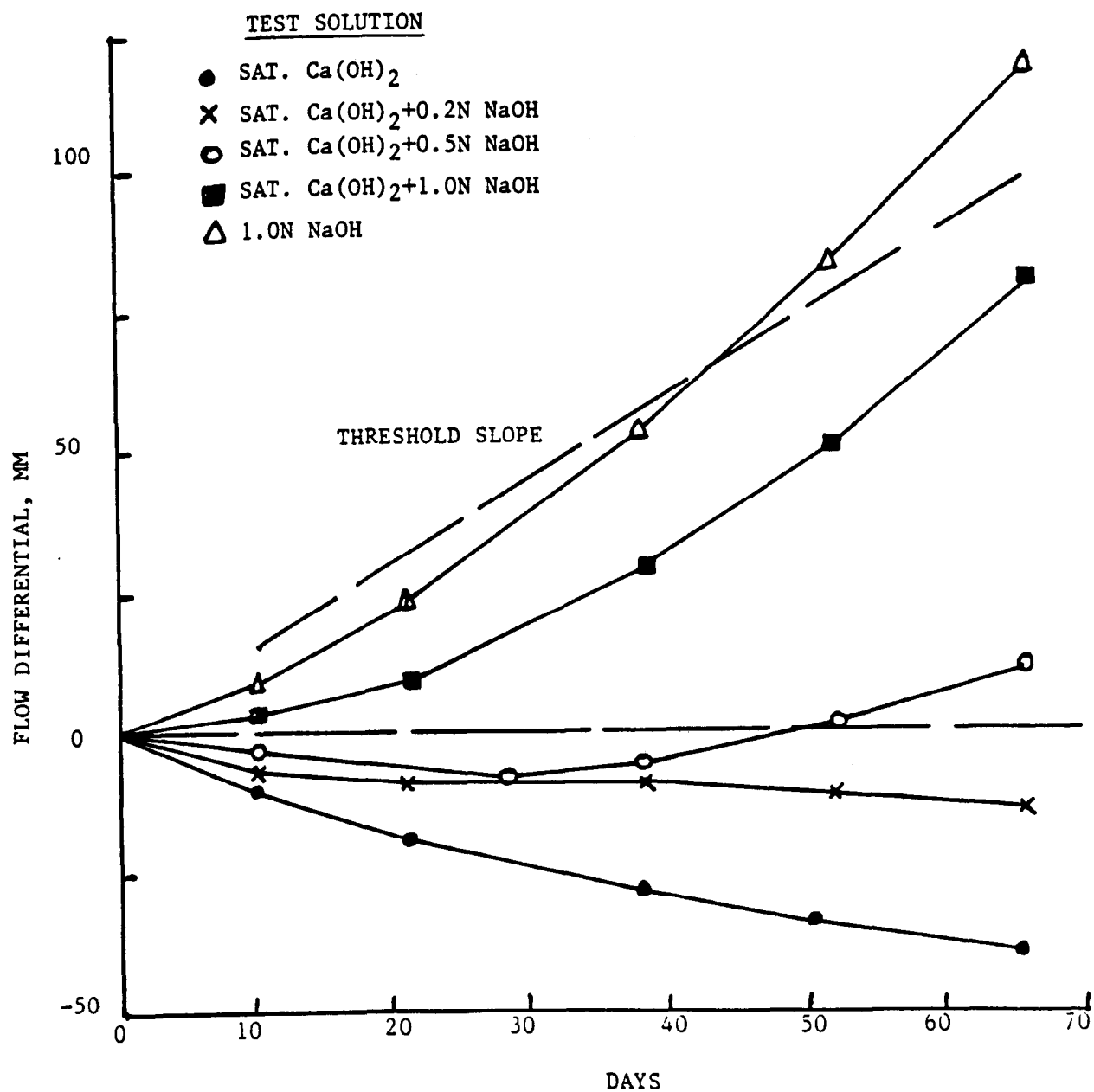


Figure E1. — Effect of NaOH concentration on flow.

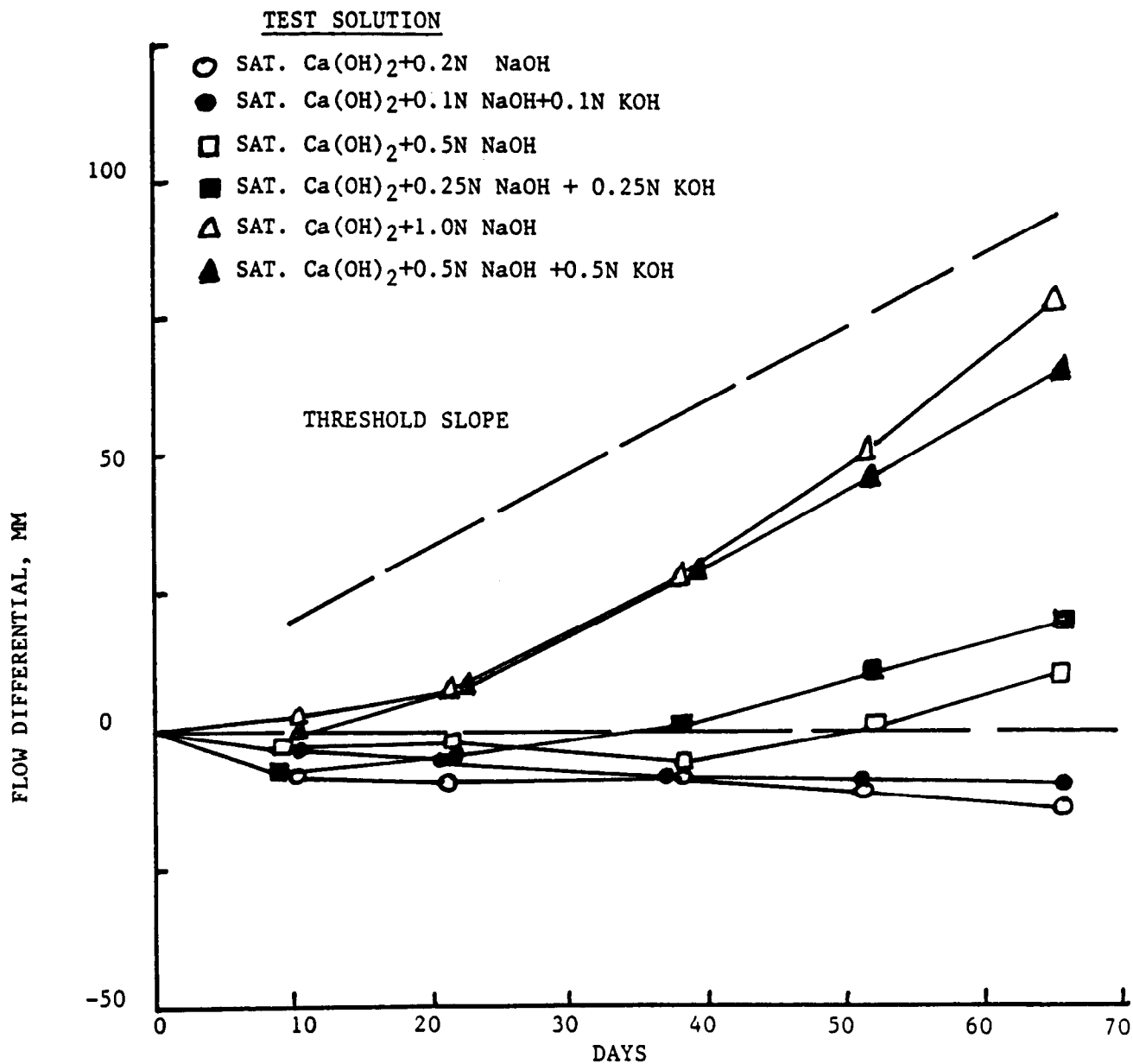


Figure E2. — Effect of NaOH and KOH concentration on flow.

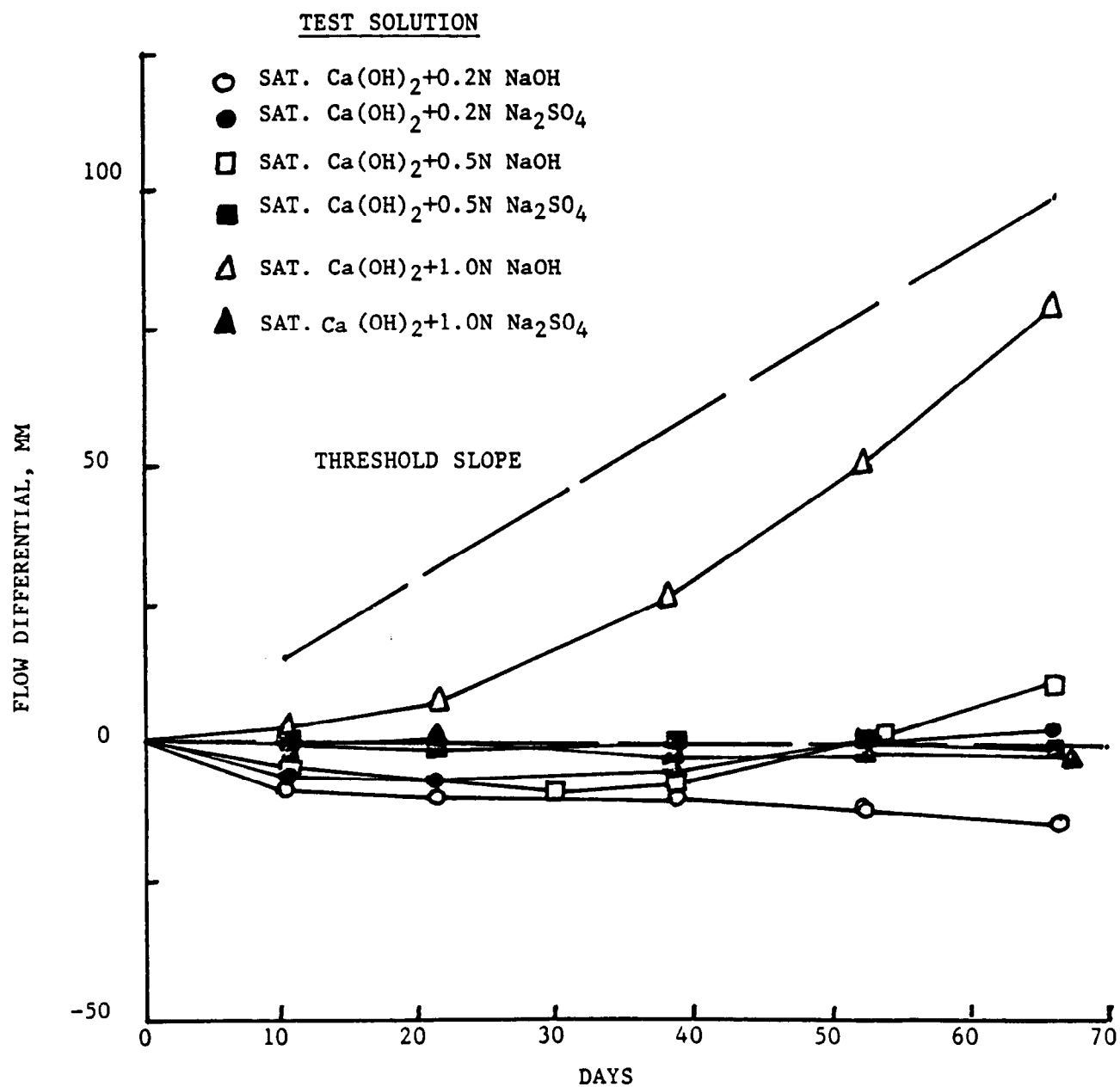


Figure E3. — Comparison of effect of  $\text{OH}^-$  and  $\text{SO}_4^{2-}$  concentration on flow rate.

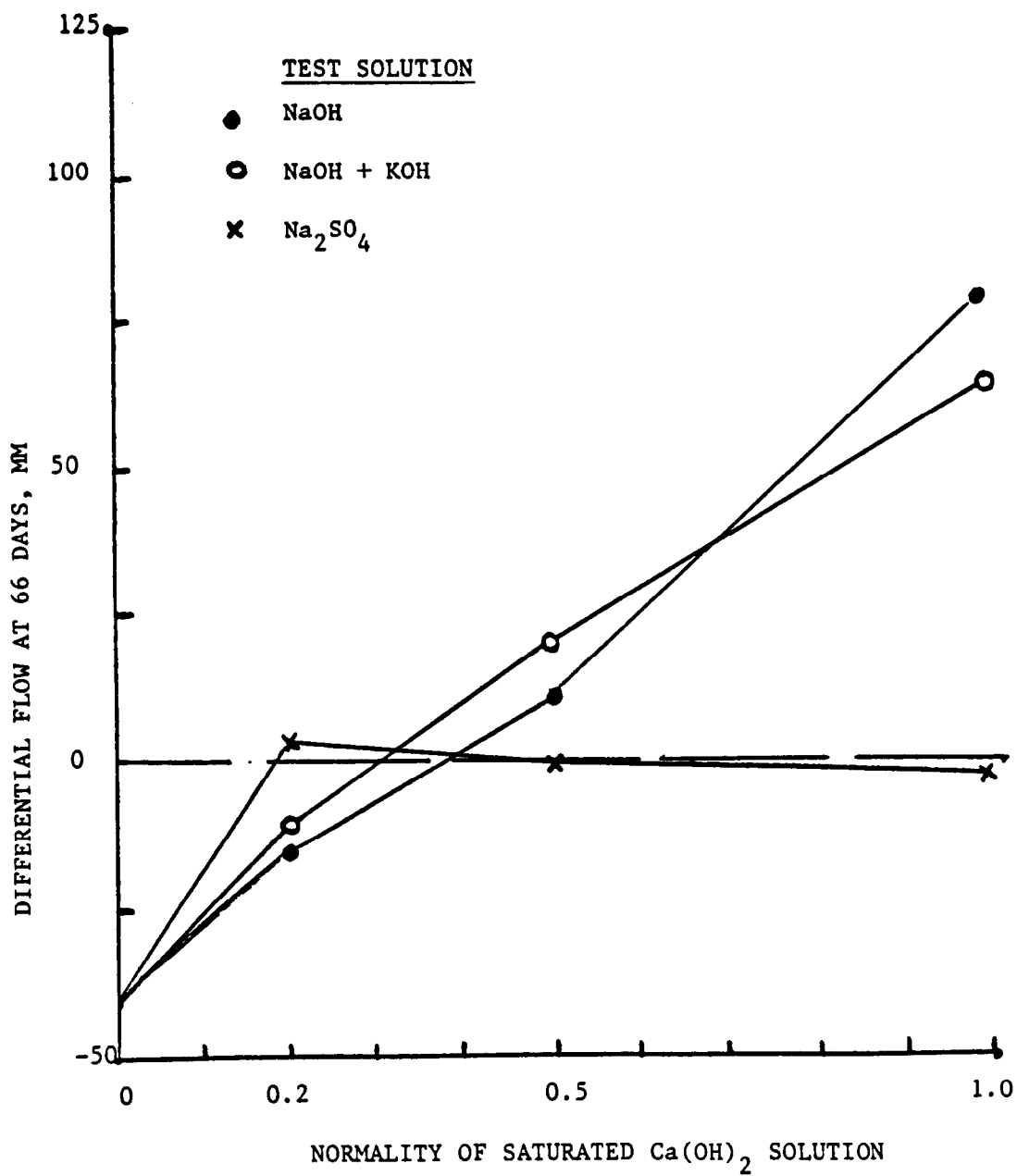


Figure E4. — Effect of concentration of  $\text{OH}^-$  or  $\text{SO}_4^{2-}$  concentration on flow rate.

GPO 830-484



### **Mission of the Bureau of Reclamation**

*The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.*

*The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.*

*Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.*

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-7923A, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.